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ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF GEOPHYSICAL SURVEY DATA WITH SPECIAL APPLICATION TO CAVITY DETECTION

by

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Errata Sheet

No. 1

ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR
INTERPRETATION OF GEOPHYSICAL SURVEY DATA WITH
SPECIAL APPLICATION TO CAVITY DETECTION

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1. Page 14, paragraph 7, line 7, and Equation 1 (line 8), should be changed to read:

calculate an apparent resistivity ρ_A

$$\rho_A = K_G \left(\frac{\Delta V}{I} \right) \quad (1)$$

2. Page 14, paragraph 7, line 11, should be changed to read:

$$K_G = 2\pi a ; \text{ and for the Schlumberger array } K_G = \pi s \left[(L/s)^2 - (1/4) \right] ,$$

3. Page 14, paragraph 7, line 17, should be changed to read:

$$\pi r n(n^2 - 1) , \text{ where } r = C_1 C_2 = P_1 P_2 \text{ and } C_1 P_1 = C_2 P_2 = nr .$$

4. Page 68, paragraph 66, line 13, should be changed to read:

and Equation 4 can be written

5. Page 72, paragraph 70, line 5 on this page, should be changed to read:

where $f^D(x)$ denotes the discrete profile data set. That is, two

6. Page 93, paragraph 98, line 16 on this page, should be changed to read:

gradient model in Figure 49a, could now be determined by using TALGRAD

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Presented are results of an effort directed toward the improvement of geophysical data acquisition, processing, and interpretation. Much of the discussion centers around the adaptation of existing or the development of new computer programs and their methodologies for processing and interpreting data acquired from electrical resistivity, microgravity, and seismic methods. Three programs for processing and interpreting electrical resistivity are discussed: (a) RESDIR computes the apparent resistivity as a (Continued)			

20. ABSTRACT (Continued).

function of electrode spacing for a given model of vertical subsurface resistivity variations; (b) RESINV calculates the model of vertical subsurface resistivity variation given the apparent resistivities acquired in the field; and (c) RESDAT is a general purpose resistivity program which handles data acquired from horizontal profiling and vertical sounding surveys.

Three programs used in conjunction with microgravity surveys are documented: (a) TIDES computes the theoretical variation in gravity caused by earth tides at any location; (b) TALGRAD calculates gravity and gravity-gradient profiles across two-dimensional subsurface models; and (c) HILBERT computes the Hilbert transform which is used to determine the vertical velocity gradient. Two gravity methodologies presented describe: (a) a technique which reduces errors in microgravity surveying through use of optimal gravity station schemes, and (b) the use of polynomial surface fitting for determination of the required field component from a set of data.

Several computer programs for processing and interpretation of seismic refraction and crosshole survey data are documented. Four programs which digitize, process, and interpret analog seismic records are presented. These programs expedite the processing of this type of data. In addition, REFRDIR and REFRINV were developed to aid in data interpretation of refraction data. Changes which made an existing computer program, CROSSHOLE, an interactive time-sharing program are documented.

Recommendations are made toward achievement of higher goals aimed at automatic data processing and interpretation of geophysical data.

PREFACE

The study reported herein was performed during the period October 1978 to May 1982 under Department of the Army Project No. 4A161102AT22, "Research in Soil and Rock Mechanics," Task AO, Work Unit 002, "Analytical and Data Processing Techniques for Interpretation of Geophysical Properties."

The work was performed by Messrs. Dwain K. Butler, Ronald E. Wahl, and Donald E. Yule, Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss.; Mr. Donald E. Barnes, Geomechanics Division, Structures Laboratory, WES; and Dr. Anthony F. Gangi, Department of Geophysics, Texas A&M University, College Station, Tex., under the direct supervision of Dr. Arley G. Franklin, Chief, EE&GD, and the general supervision of Dr. William F. Marcuson III, Chief, GL. The work by Dr. Gangi was performed under Contract No. DACA39-79-M-0074 and involved preparing and documenting the computer programs REFRDIR and REFRINV. Mr. Wahl developed the computer programs SEISDIG, SEISPLOT, and REFINT. The computer program DOMER was written by Mr. Yule. Mr. Barnes developed the computer programs PLOT2 and PLOTLL and provided assistance in the use of these programs. This report was prepared by Mr. Butler.

The study was closely coordinated with work planned by Mr. Joseph R. Curro, Jr., Chief, Field Investigations Group, EE&GD, GL, under CWIS Work Unit 31150, "Remote Delineation of Cavities and Discontinuities in Rock," and by Mr. Butler under DA Project No. 4A161101A91D, "Assessment of Microgravimetry for Geotechnical Applications."

COL Tilford C. Creel, CE, was Commander and Director of WES during the conduct of this study. Mr. Fred R. Brown was Technical Director.

CONTENTS

	<u>Page</u>
PREFACE	1
CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT	4
PART I: INTRODUCTION	5
Background	5
Applications of Geophysical Methodology	5
Geophysical Data Sources	6
Purpose	11
Scope	11
PART II: SURFACE ELECTRICAL RESISTIVITY METHODS	14
Background	14
RESDIR: A Computer Program for Solution of the Direct Problem in Resistivity Sounding	16
RESNIV: A Computer Program for Solution of the Inverse Problem in Resistivity Sounding	20
RESDAT: A General Purpose Resistivity Data Processing Program	28
PART III: MICROGRAVIMETRIC TECHNIQUES	41
Background	41
Gravity Station Occupation Schemes	44
Use of Theoretical and Measured Earth-Tide Records	46
TIDES: A Computer Program for Computing the Theoretical Earth Gravity Tide	48
Polynomial Surface-Fitting for Regional- Residual Separation	50
Gravity Interpretation by Two-Dimensional Polygonal Cross-Section Models	57
TALGRAD: A Computer Program for Computing Gravity and Gravity-Gradient Profiles Over Two- Dimensional Models	58
Determination of Vertical Gravity-Gradient Profiles by a Hilbert Transform Procedure	61
HILBERT: A Computer Program for Computing the Discrete Hilbert Transform of Profile Data	67
Manatee Springs Microgravimetric and Gravity- Gradient Survey	76
Gravity-Gradient Analysis of a Selected Gravity Profile Across Dry Lake Valley, Nev.	84
PART IV: SEISMIC METHODS	94
Background	94
Minicomputer Processing of Seismic Refraction Data	99

	<u>Page</u>
Computer Modeling and Interpretation of Seismic	
Refraction data	108
CROSSHOLE: Time-Sharing Version	118
PART V: SUMMARY AND FUTURE PLANS	124
Summary	124
Future Plans	125
REFERENCES	127
APPENDIX A: RESDIR LISTING	A1
APPENDIX B: PLOT2 AND PLOTLL INSTRUCTIONS AND LISTINGS	B1
APPENDIX C: RESINV LISTING	C1
APPENDIX D: RESDAT LISTING	D1
APPENDIX E: TIDES LISTING	E1
APPENDIX F: TALGRAD LISTING	F1
APPENDIX G: HILBERT LISTING	G1
APPENDIX H: SEISDIG, SEISPLOT, REFINT, AND DOMER LISTINGS	H1
APPENDIX I: REFRDIR EXAMPLE AND LISTING	I1
APPENDIX J: REFRINV EXAMPLE AND LISTING	J1
APPENDIX K: CROSSHOLE LISTING	K1

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres

ANALYTICAL AND DATA PROCESSING TECHNIQUES FOR INTERPRETATION OF
GEOPHYSICAL SURVEY DATA WITH SPECIAL APPLICATION TO
CAVITY DETECTION

PART I: INTRODUCTION

Background

1. In foundation investigations for permanent military facilities ranging from the common post facilities such as hospitals, barracks, etc., to underground command, control, and communication (C³) facilities, there is a need for accurate information on subsurface stratigraphy, structure, and physical properties. Presently, this information is obtained through a combination of drilling, laboratory testing, and geophysical testing. Emphasis in the field investigation is on drilling and logging of borings which is a relatively expensive procedure. Often as much as five percent of the construction cost is expended in geotechnical investigations for military facilities and over half of this is spent in the field. Geophysical methods have the potential for reducing these costs; however, the full potential of geophysical methods to reduce the number of borings required is not presently being utilized partly because processing and interpretation of geophysical data in the U. S. Army Corps of Engineers usually is done manually. This has evolved primarily because judgment is required in the data reduction and interpretation process. The manual methods are very labor-intensive, and frequently there are considerable delays in reporting survey results due to processing "backlogs." Also, since hand methods are being used, recent developments in wave propagation and potential field theory, which involve large amounts of computation and could assist in the interpretation of data, are not being utilized.

Applications of Geophysical Methodology

2. The various types of surface and subsurface geophysical methods are reviewed in Engineer Manual 1110-1-1802 (Department of the

Army, 1979). This report will concentrate on three of the surface geophysical methods and one cross-borehole method:

- a. Electrical resistivity.
- b. Microgravimetry.
- c. Seismic refraction.
- d. Crosshole seismic method.

3. In addition to foundation investigations to aid in facility design and construction, geophysical methods are applicable to post-construction facility development functions, such as groundwater exploration, and monitoring functions, such as groundwater contamination detection and subsurface intrusion prevention and detection. Table 1 summarizes the applicability of the above four geophysical methods to various military facility design, construction, development, and monitoring functions.

Geophysical Data Sources

4. As described in the Preface, the work described here was closely coordinated with two other research efforts. In this way, efforts under the three projects were complementary, and relevant field data were available for processing and interpretation using techniques developed during the present work. Specifically, the field efforts involved the evaluation of some 28 geophysical techniques for cavity detection and delineation at two natural cavity test sites in Florida, and many of the examples used in this report are drawn from the data from these sites. Figure 1 is a location map showing the two sites. The Medford Cave site has a relatively shallow (<10 m) air-filled cavity system; Figure 2 shows a plan view of the known cave system and the geophysical survey area at the site. The Manatee Springs site has a deeper (~30 m) water-filled cavity system; Figure 3 is a plan map of the known cavity system and the area used for the geophysical surveys. Cavity detection and delineation is considered a particularly appropriate application since the presence of cavities, either natural (e.g., solution cavities in carbonates) or man-made (abandoned mine workings or

Table 1
Applicability of Geophysical Methods

Use of Method	Geophysical Method			
	Seismic Refraction	Seismic Crosshole	Electrical Resistivity	Microgravity
Site selection	1	4	1	1
Stratigraphy and lithology definition	1	1	1	3
Depth to top of rock	1	4,5	1,2	1,2
Geologic structure determination	1,2	2,3	1,2	1
Groundwater exploration and assessment	1	4,5	1	1,2
Groundwater contamination detection	5	5	1	5
Construction materials exploration (sand and gravel)	2	4,5	1	2
Facility monitoring/perimeter integrity	3,4	4	1	1

NOTE: 1 - Primary usefulness
 2 - Secondary usefulness
 3 - Has indirect or limited usefulness
 4 - Could be used but not best or practical approach
 5 - Not applicable
 2,3 - Indicates a range of 2 to 3, or that applicability may vary depending on circumstances

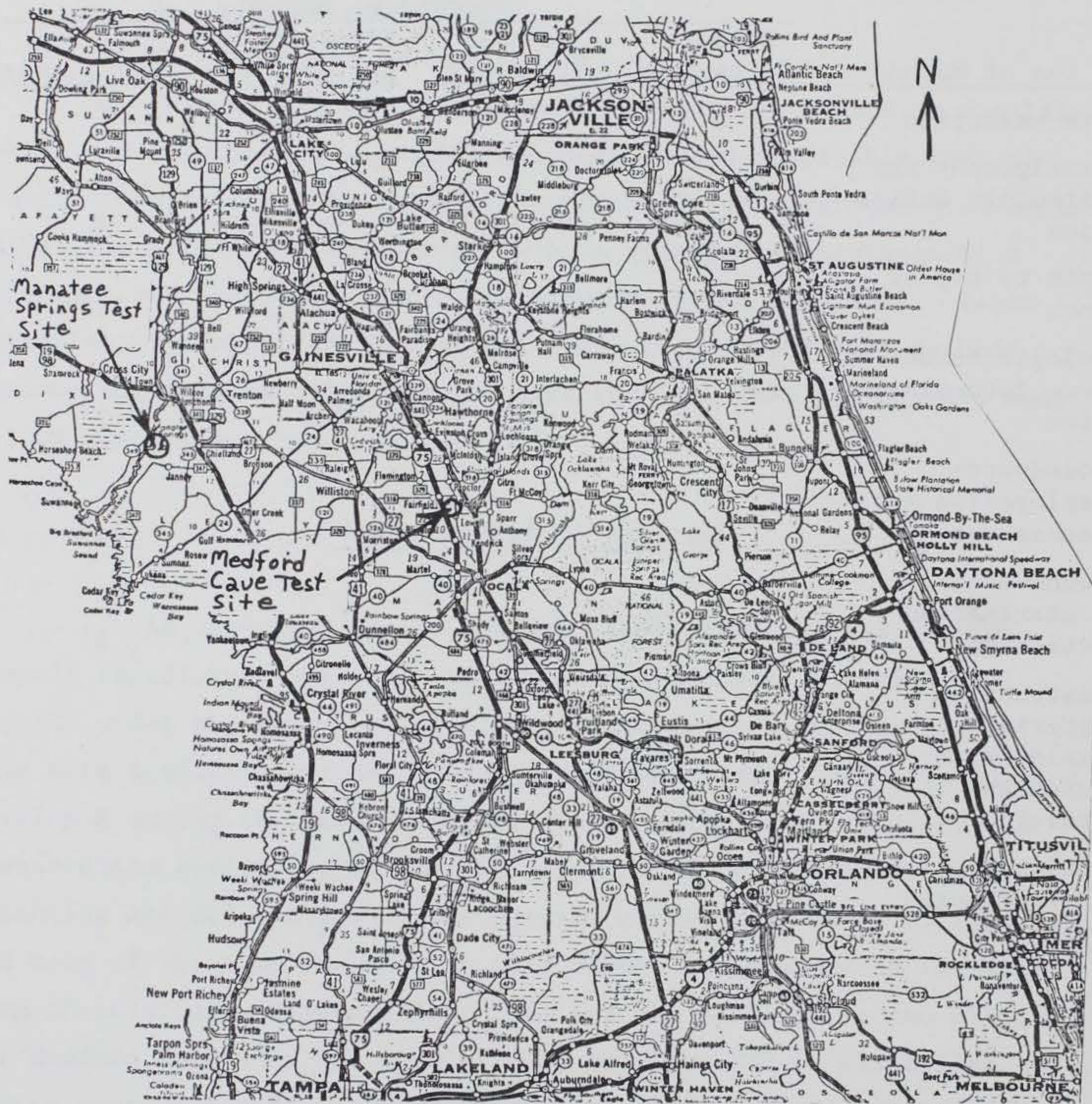


Figure 1. Map showing locations of Medford Cave and Manatee Springs test sites

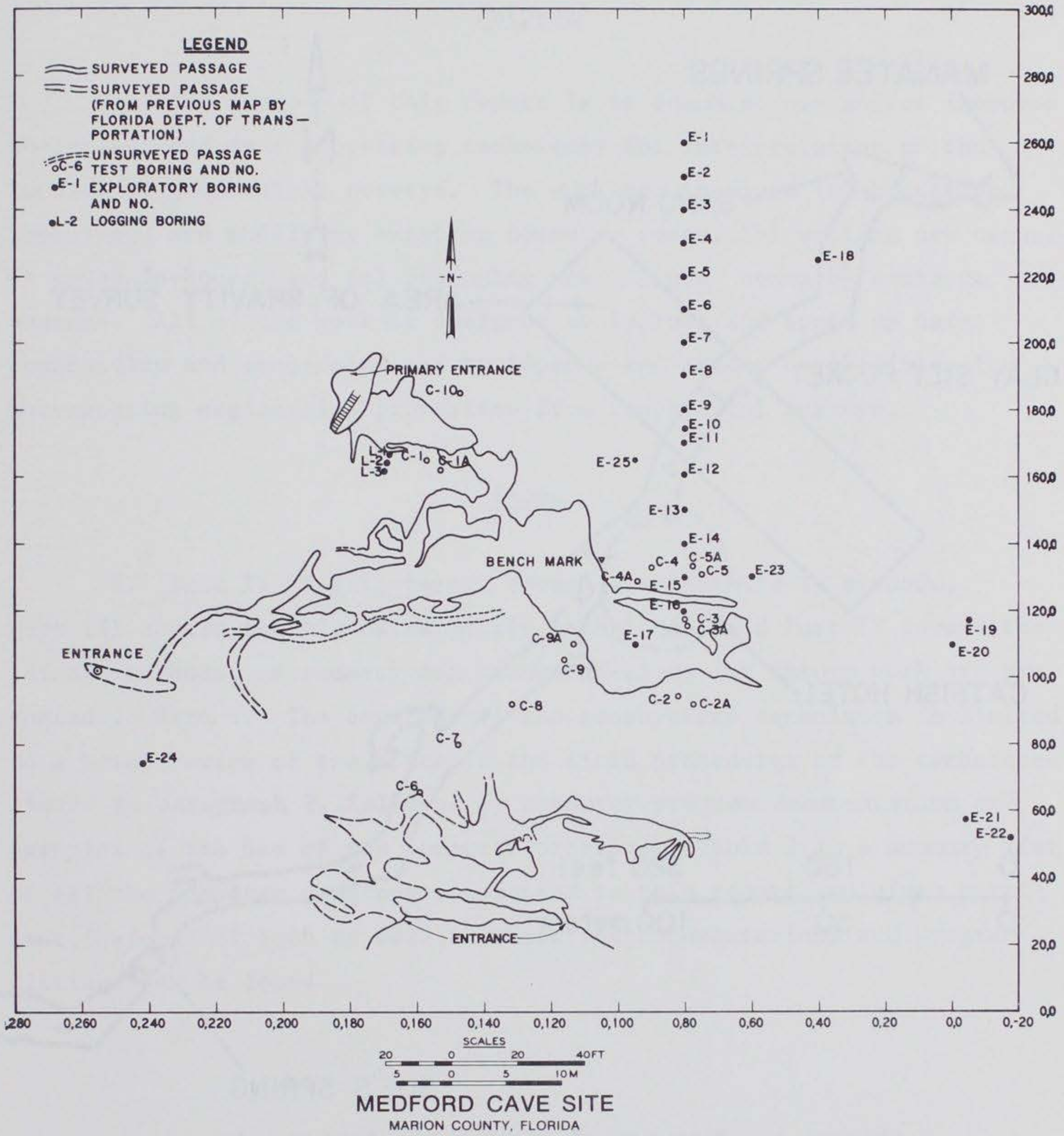


Figure 2. Plan map of the Medford Cave site, Marion County, Fla.

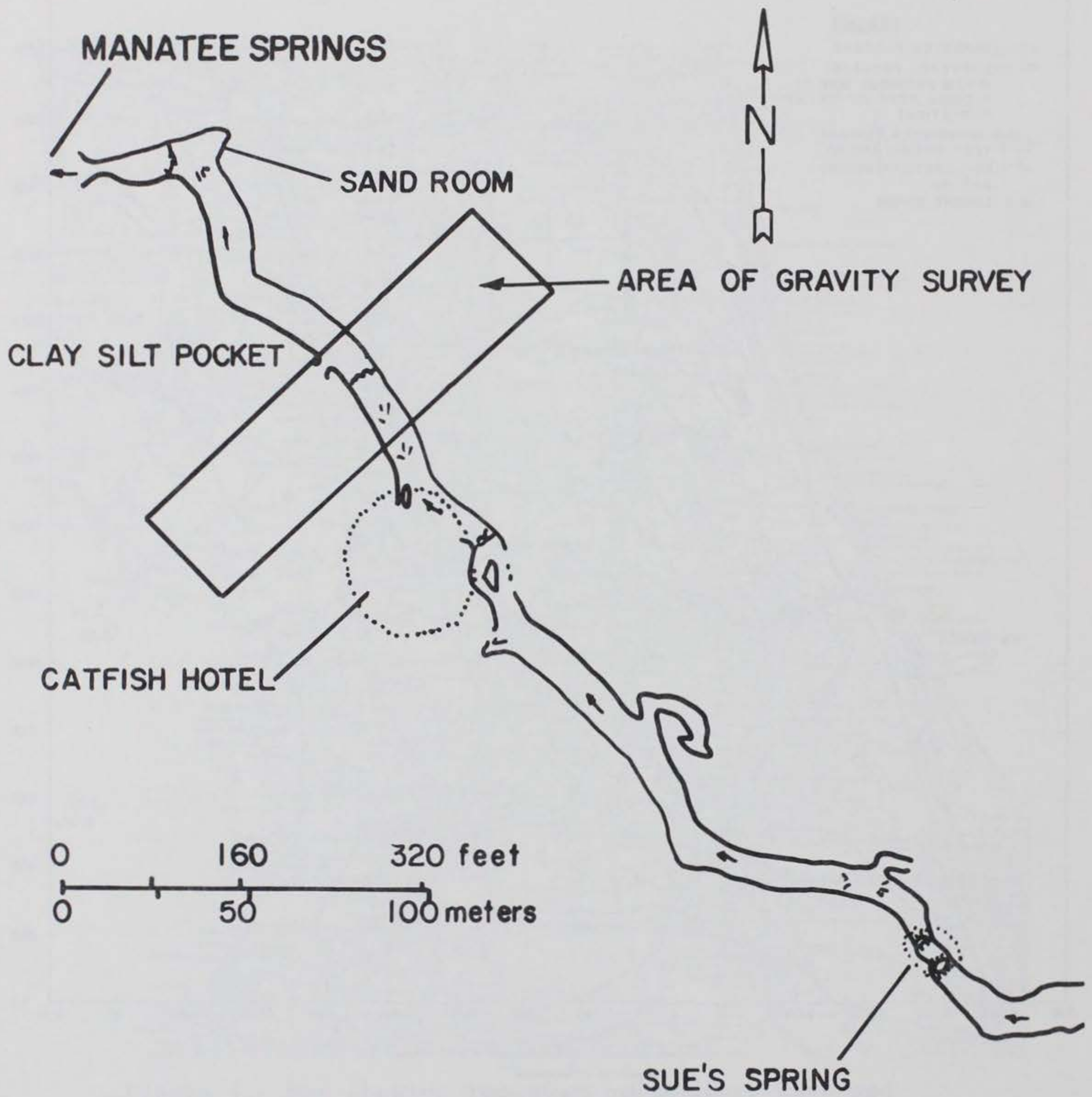


Figure 3. Plan map of the Manatee Springs site, Levy County, Fla.

clandestine tunnels) presents problems for facility foundations as well as for base perimeter security.

Purpose

5. The purpose of this report is to document new and/or improved analytical and data processing techniques for interpretation of the results of geophysical surveys. The work has involved (a) acquiring, improving, and modifying existing computer codes; (b) writing new computer codes in-house; and (c) producing new computer codes by contract sources. All of the work is designed to improve and speed up data acquisition and processing and to improve and extend capabilities for interpreting engineering properties from geophysical surveys.

Scope

6. Part II of this report covers the resistivity methods, Part III covers the microgravimetric techniques, and Part IV covers the seismic methods. A summary and recommendations for future work are presented in Part V. The coverage of the geophysical techniques is limited to a brief review of the concepts and field procedures of the techniques listed in paragraph 2, followed by computer program documentation and examples of the use of the computer programs. Table 2 is a summary list of all the computer programs documented in this report and gives pertinent features of each as well as where the documentations and program listings can be found.

Table 2
Summary List of Geophysical Computer Programs

<u>Program Name</u>	<u>Primary Function</u>	<u>Program Documenta- tion, Part</u>	<u>Program Listing, Appendix</u>	<u>Language</u>	<u>Operating Mode</u>	<u>Equipment/Facility Requirements</u>	<u>Comments</u>
RESDIR	Compute resistivity sounding data for specified model	II	A	FORTRAN IV	T/S*	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
RESINV	Determine subsurface model from resistivity field sounding data	II	C	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
RESDAT	General purpose resistivity field data processing program	II	D	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
TIDES	Computes theoretical earth gravity tide	III	E	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
TALGRAD	Computes gravity and gravity gradients for polygonal cross section models	III	F	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
HILBERT	Computes Hilbert transform of discrete profile data	III	G	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
SEISDIG	Digitize analog seismic records	IV	H	BASIC	M/C††	Tektronix 4051 Minicomputer Tektronix Hard Copy Unit or Printer† Tektronix Digital Plotter Tektronix Graphics Tablet/ Four Button Cursor	1

(Continued)

- * Time sharing
- ** Currently operational on Honeywell DPS-1
- † Optional
- †† On-line mini/micro computer facility
- 1 Easily adapted to other mini/micro computer systems

Table 2 (Concluded)

Program Name	Primary Function	Program Documentation, Part	Program Listing, Appendix	Language	Operating Mode	Equipment/Facility Requirements	Comments
SEISPLOT	Plot Seisdig data files	IV	H	BASIC	M/C	Tektronix 4051 Minicomputer Tektronix Digital Plotter	1
REFINT	Interpret seismic refraction time-distance plots	IV	H	BASIC	M/C	Tektronix 4051 Minicomputer Tektronix Hard Copy Unit or Printer† Tektronix Graphics Tablet/ Four Button Cursor	1
DOMER	Processes Rayleigh-wave data from analog refraction records	IV	H	BASIC	M/C	Tektronix 4051 Minicomputer Tektronix Hard Copy Unit or Printer Tektronix Digital Plotter Tektronix Graphics Tablet/ Four Button Cursor	1
REFRDIR	Computes time-distance data for specified model	IV	I	FORTRAN IV	T/S*	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	
REFRINV	Determines subsurface model from seismic refraction field data	IV	J	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal	
CROSSHOLE	Interprets crosshole seismic survey data	IV	K	FORTRAN IV	T/S (or Batch)	Mainframe Computer** T/S Terminal	2
PLOT 2	Produces on-line plot at T/S terminal location with linear axes	App B	B	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	3
PLOTLL	Produces on-line plots at T/S terminal location with logarithmic axes	App B	B	FORTRAN IV	T/S	Mainframe Computer** T/S Terminal Tektronix Digital Plotter†	3

* Time sharing

** Currently operational on Honeywell DPS-1

† Optional

†† On-line mini/micro computer facility

1 Easily adapted to other mini/micro computer systems

2 Only selected options have been reformatted for output on T/S Terminal

3 Uses standard Cal/Comp instruction commands

Background

7. All surface electrical resistivity methods considered in this section involve linear four-electrode geometries (arrays). The four most common electrode arrays are illustrated in Figure 4. In each of the four arrays, an electrical current I is input to the ground at electrodes C_1 and C_2 . Electrodes P_1 and P_2 are used to measure a potential difference ΔV . The following equation can be used to calculate an apparent resistivity ρ_A

$$\rho_A = K_G \frac{\Delta V}{I} \quad (1)$$

where K_G is a geometric factor which depends on the array type and electrode spacings within the array. For the Wenner array (Figure 4a), $K_G = 2\pi a$; and for the Schlumberger array $K_G = \pi s \left[(L/s)^2 - 1/4 \right]$, where $s = P_1 P_2$ and $L = C_1 C_2 / 2$ (generally $L \geq 5s$). In the pole-dipole array, electrode C_2 is placed at effective infinity (generally $C_2 P_2 > 5$ to 10 times the maximum value reached by $C_1 P_2$ during a survey is sufficient); and $K_G = 2\pi R_1 R_2 / (R_2 - R_1)$, where $R_1 = C_1 P_1$ and $R_2 = C_1 P_2$ ($R_2 - R_1 = P_1 P_2$). Finally, for the dipole-dipole array, $K_G = \pi r n (n^2 - 1)$, where $r = C_1 C_2 = P_1 P_2$ and $C_1 P_1 = C_2 P_2 = nr$.

8. The resistivity given by Equation 1 is called an apparent resistivity since it may not actually be the true resistivity of any of the subsurface materials. This fact can be illustrated by a conceptual example: consider a layer of soil over a bedrock which is very thick. If, say, a Schlumberger or Wenner electrode array is used to study the example just presented, the following facts can be stated: (a) for electrode spacings a or L much smaller than the soil layer thickness, the measured apparent resistivity (ρ_A) approaches the true resistivity of the soil (ρ_1); (b) for electrode spacings a or L much greater than the soil layer thickness, the apparent resistivity approaches the true resistivity of the bedrock (ρ_2); and (c) for a or L values

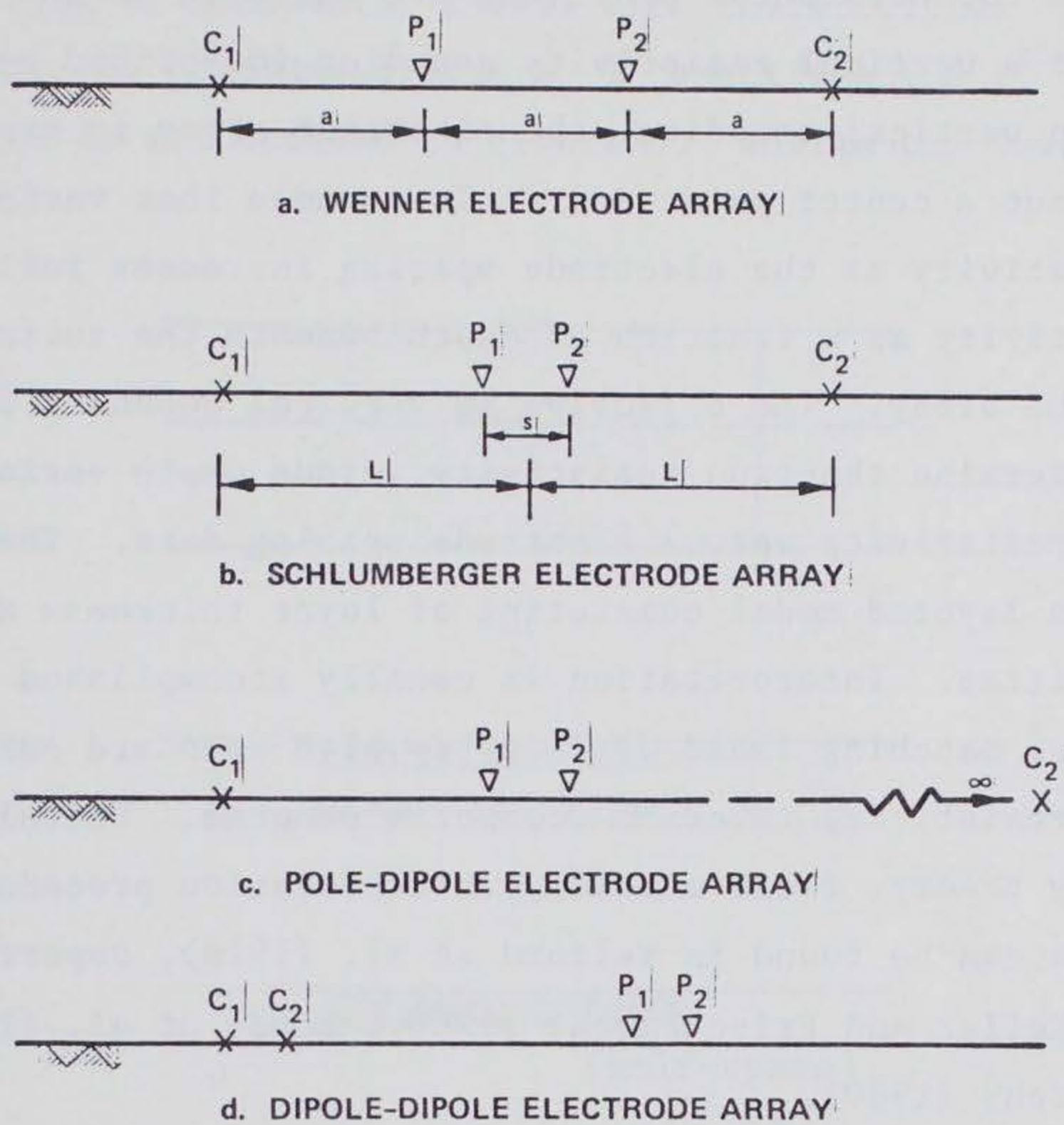


Figure 4. Four commonly used resistivity electrode arrays

between these two extremes, the apparent resistivity will be intermediate in value (i.e., the measured apparent resistivity will be a volume average of ρ_1 and ρ_2 , with the volume included in the measurements increasing with a and L).

9. Two types of surface resistivity surveys can be conducted, and these surveys will be termed horizontal profiling and vertical soundings. In horizontal profiling surveys, electrode spacings are selected and the entire array is moved along the surface keeping the spacings constant. If a set of parallel profile lines is surveyed in this manner, the result will be a grid of apparent resistivity values over an area for a constant electrode geometry; this grid of data can then be contoured to produce a resistivity map. Horizontal resistivity profiling is designed to investigate lateral geologic variations above

an essentially constant depth of investigation. Frequently the electrode spacings for horizontal profiling are selected on the basis of the results of a vertical resistivity sounding (described below).

10. In vertical sounding, the electrode array is expanded symmetrically about a center point and it is assumed that variations in apparent resistivity as the electrode spacing increases reflect changes in true resistivity as a function of depth beneath the surface point of symmetry of the array. The objective in vertical sounding interpretation is to determine the true resistivity versus depth variation from the apparent resistivity versus electrode spacing data. The result will generally be a layered model consisting of layer thickness and associated true resistivities. Interpretation is usually accomplished by curve matching (i.e., matching field data curves with standard curves) or by the use of a resistivity inversion computer program. Useful discussions of resistivity theory, field methods, interpretation procedures, and case histories can be found in Telford et al. (1976), Department of the Army (1979), Keller and Frischknecht (1966), Zohdy et al. (1974), and Butler and Murphy (1980).

11. In this section, three computer programs will be described which assist in the processing and interpretation of resistivity field data. The first two programs, RESDIR and RESINV, are used for interpreting vertical resistivity sounding surveys. The third program, RESDAT, is a general purpose resistivity processing program. Also, examples of the use of the processed and interpreted resistivity results will be presented as illustrations and as suggestions for future work. All of the programs are written in FORTRAN IV for use on the U. S. Army Engineer Waterways Experiment Station (WES) Time-Sharing system; use of the plotting options requires a Tektronix Digital Plotter on-line at the terminal.

RESDIR: A Computer Program for Solution of the
Direct Problem in Resistivity Sounding

12. The direct or forward problem in electrical resistivity sounding consists of specifying a resistivity model and then calculating

the apparent resistivities which would be observed by a given electrode array on the surface of the model. For present purposes, the class of models consisting of horizontal layers with resistivities ρ_i and thicknesses h_i is considered, where i specifies the i^{th} layer; this class of models is illustrated in Figure 5. Unlike the inverse problem

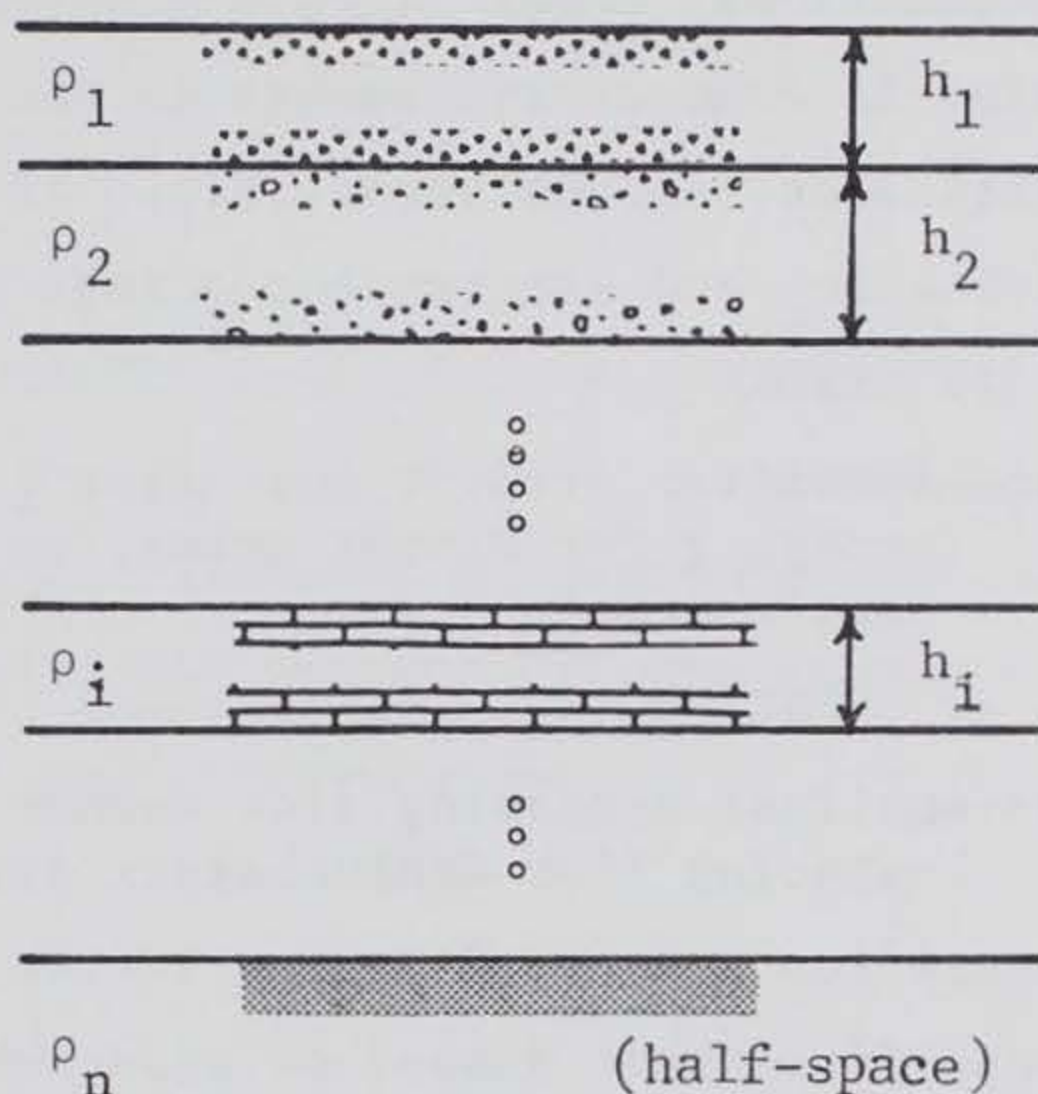


Figure 5. Resistivity model, n-layers with horizontal interfaces

of deducting a possible model directly from field resistivity sounding data, the direct resistivity sounding problem is unique; i.e., for a given electrode geometry and resistivity model, there is only one possible sounding curve.

13. RESDIR is a FORTRAN computer program which solves the direct problem in resistivity sounding using linear filter theory (Ghosh, 1971a, b). The filters were derived by Davis (1979a) and the program described in Davis (1979a, b) and Mooney (1979). The program was adopted for use on the WES computer time-sharing system and an output plotting option was added. For a given electrode array, Wenner, Schlumberger, or axial dipole-dipole, the program computes and plots the apparent resistivity sounding curve. Beginning with a user-specified initial electrode

spacing, the apparent resistivity values are computed at six points per decade of electrode spacing. A listing of RESDIR is presented in Appendix A.

Input data

14. All data are input in a free-field format with prompting messages; i.e., the specified parameters are input consecutively, separated by commas. Individual input lines and parameters are described below and also in comment statements in the program listing (Appendix A). The units must be consistent, e.g., if resistivities in ohm-m, then layer thicknesses and electrode spacings must lie in m.

Input No. 1: INDEX

Index--specifies array type; enter 1 for Schlumberger array, 2 for Wenner array, or 3 for dipole-dipole array.

Input No. 2: SPAC, E, M

SPAC--smallest a-spacing (for Wenner array), or smallest L-spacing (for Schlumberger array).

E--specifies number of layers in the chosen model.

M--specifies total number of apparent resistivity values to be calculated (at rate of six per decade beginning with SPAC)

Input No. 2A: IX

Input only for dipole-dipole array (INDEX = 3).

IX--enter 0 if r is varied (n constant) or enter 1 if n is varied (r constant).

Input No. 2B: N-values

If IX = 0, enter only one N-value

If IX = 1, enter M N-values.

Input No. 3: Model Parameters (P(I), I = 1, 2E - 1)

Enter E-1 layer thicknesses, immediately followed by E layer resistivities.

The above input sequence is repeated for additional models; normal program selection is terminated by inputting 0 (zero) for INDEX.

Program input

15. Printed output from the program consists of a listing of the input model and then a listing of the computed apparent resistivities and

corresponding electrode spacings. Optional plots of apparent resistivity versus electrode spacing for Wenner or Schlumberger arrays can be generated; either arithmetic or logarithmic plots can be selected. The plots are generated by a CALL PLOT2 (X, Yn, N) or CALL PLOTLL (X, Y, N) command, where X and Y are the parameters to be plotted and N is the number of values. PLOT2 and/or PLOTLL are used in nearly all the programs in this report and are documented in Appendix B; the plot specification input sequence is the same for all programs in this report.

Examples

16. RESDIR can be used to generate sounding curves for hypothetical field situations and as an aid in interpreting field sounding data.

17. Example 1. Consider the hypothetical two-layer case shown in Figure 6; the plots demonstrate the appearance of the sounding curves

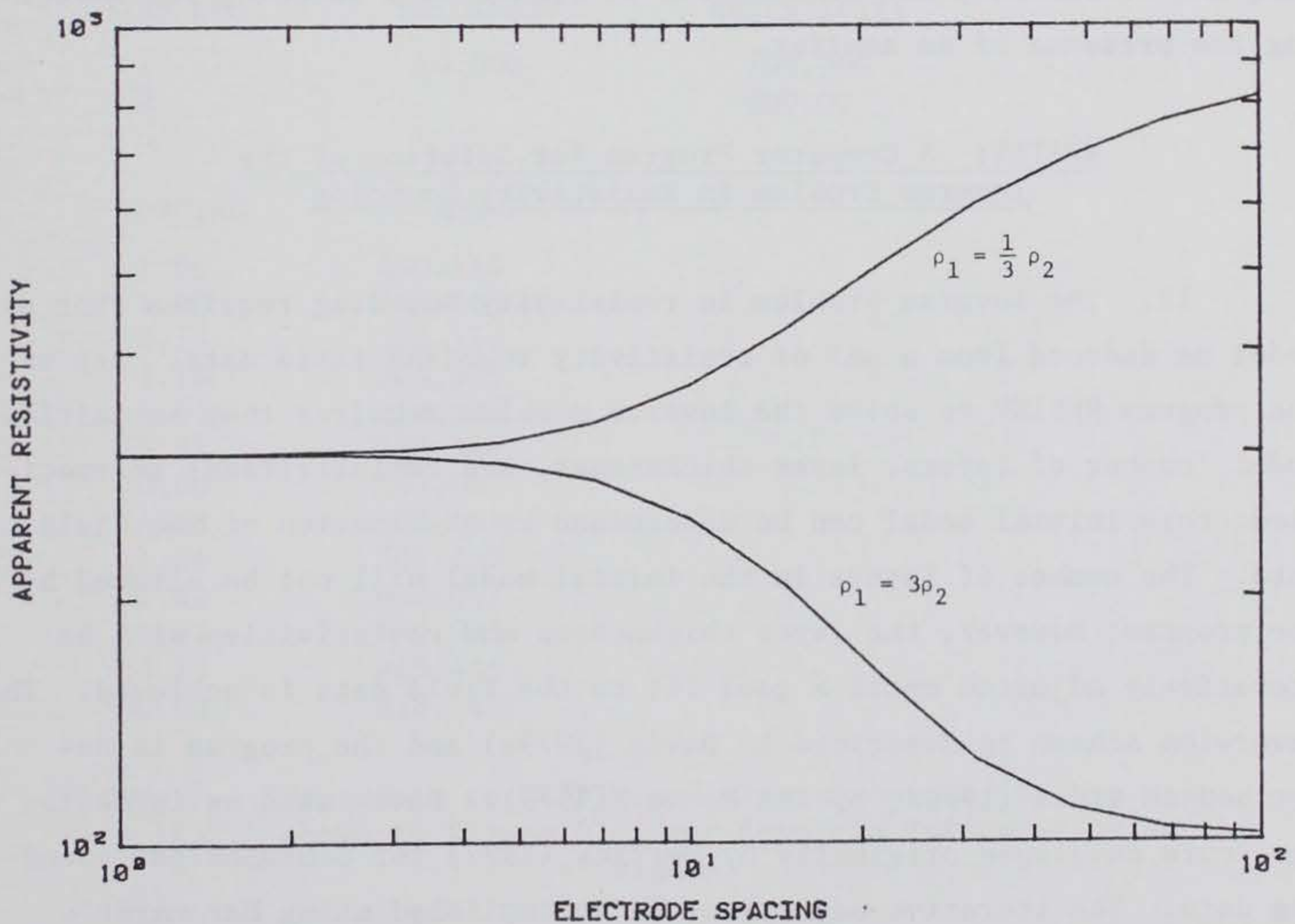


Figure 6. Two-layer resistivity sounding curves, Wenner electrode array, computed using RESDIR (For both cases, $h_1 = 10$ m and $\rho_1 = 300$ ohm-m.)

using a Wenner array for two cases, where $\rho_1 = 1/3\rho_2$ and where $\rho_1 = 3\rho_2$; the layer thickness is the same for both cases. The input data and program output are shown in Figure 7 for the case where $\rho_1 = 1/3\rho_2$.

18. Example 2. As an example of the use of RESDIR for generation of sounding curves for hypothetical field situations, consider the three-layer model in Figure 8. The objective of this model is to simulate the case of an alluvial aquifer above a resistant basement; i.e., layer 1 represents an unsaturated sandy soil, layer 2 represents the alluvial aquifer (saturated sandy soil), and layer 3 represents the resistive basement rock. The aquifer thickness is constant at 10 m, and three different depths to the top of the aquifer are considered. Sounding curves for the three cases using a Schlumberger array are also shown in Figure 8. Results such as shown in Figure 8 could be used for assessing the feasibility and limitations of resistivity sounding for detecting the presence of an aquifer.

RESINV: A Computer Program for Solution of the
Inverse Problem in Resistivity Sounding

19. The inverse problem in resistivity sounding requires that a model be deduced from a set of resistivity sounding field data. Use of the program RESINV to solve the inverse problem requires that an initial model (number of layers, layer thicknesses, and resistivities) be specified; this initial model can be determined by examination of the field data. The number of layers in the initial model will not be altered by the program; however, the layer thicknesses and resistivities will be iteratively adjusted until a good fit to the field data is achieved. The inversion scheme is described in Davis (1979a) and the program is described in Davis (1979a, b) and Mooney (1979). Davis used an inversion procedure developed originally by Merrick (1977) for Schlumberger sounding data. The iterative adjustment is accomplished using Marquardt's algorithm (Marquardt, 1963), which is an optimized combination of Newton-Gauss and gradient inversion methods.

INPUT NO. 1---INDEX (ARRAY TYPE)

=2

INPUT NO. 2--SPAC,E,M

=1,2,13

INPUT NO. 3, MODEL PARAMETERS, THICKNESSES(H) AND RESISTIVITIES(R)---H
(1),H(2),.....,H(E-1),R(1),.....,R(E)

=10,300,900

APPARENT RESISTIVITY VALUES

WENNER ARRAY

2 LAYER MODEL.

LAYER NO.	THICKNESS	RESISTIVITY
1	10.000	300.000
2		900.00

SPACING	RHO
1.00	300.114
1.47	300.369
2.15	301.155
3.16	303.505
4.64	310.133
6.81	326.964
10.00	363.097
14.68	425.195
21.54	509.295
31.62	602.067
46.42	689.895
68.13	763.446
100.00	818.245

Figure 7. Input data to RESDIR and program output for the case $\rho_1 = 1/3\rho_2$ shown in Figure 6 (User input is indicated by an '=' sign.)

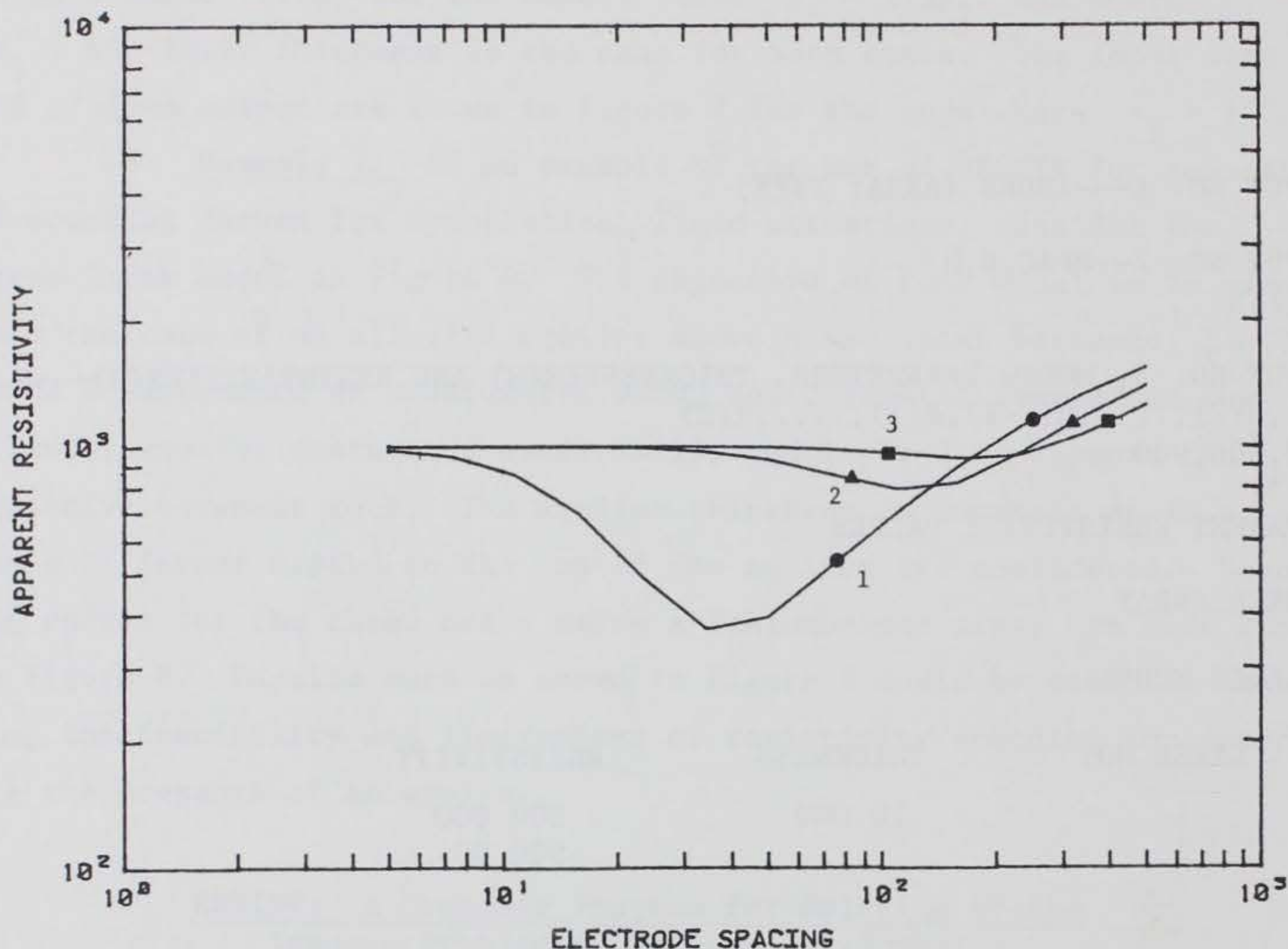


Figure 8. Schlumberger array sounding curves for three-layer model with $\rho_1 = 1000$ ohm-m, $\rho_2 = 100$ ohm-m, $\rho_3 = 2000$ ohm-m, and $h_2 = 10$ m (Case 1-- $h_1 = 10$ m; Case 2-- $h_1 = 50$ m; Case 3-- $h_1 = 100$ m.)

20. Using the techniques of RESDIR, apparent resistivities for the initial model are computed and compared with the field data. A derivative matrix consisting of partial derivatives of apparent resistivity with respect to each model parameter is computed. Corrections to each model parameter are determined from a generalized inversion of the derivative matrix. The corrections are added to initial model and a new set of apparent resistivities and layer thicknesses are computed. This procedure is continued until the root-mean-square (rms) error falls below a specified convergence criterion.

21. Even though a given initial model may be adjusted to a final model which results in computed apparent resistivities that closely fit field data, the model is not unique and may not be geologically correct or even reasonable. Any independent geologic control which is known for

the site should be utilized to constrain the inversion process; any of the model parameters can be specified as fixed, as dictated by geologic control, and will not change during the inversion process. In general, the minimum number of layers required to produce the essential features of the field sounding curve should be used initially, adding layers for subsequent models only if a good fit is not achieved with the minimum number of layers. The initial model can be chosen by the use of graphical and empirical techniques, such as curve-fitting, asymptotes, and inflection points of field curves, Barnes layer method, Moore cumulative method, inverse slope method, or, in many cases, just by examination of the field-sounding curve (Hugdahl and Dahl, 1979; Barnes, 1954; Sanker Narayan and Ramanujachary, 1967; Moore, 1945; Telford et al., 1976). The examples which follow will illustrate some of these techniques. Successful use of RESINV depends to a greater extent on the particular set of data involved, the quality of the data (including lack of lateral effects* in the data), and the experience of the interpreter. The best results with RESINV will be achieved when there is good geologic control and/or when the interpreter is familiar with the geologic sequence likely to be encountered in a particular area.

Input data

22. All data are input in free-field format. A program listing for RESINV is in Appendix C. Input data requirements are as follows:

Input No. 1: INDEX

INDEX--array type; enter 1 for Schlumberger array,
2 for Wenner array, or 3 for dipole-dipole array

Input No. 2: SPAC, E, M, NN, RMSC

SPAC--smallest a-spacing (for Wenner array) or smallest
L-spacing (for Schlumberger array)

E--specifies number of layers for model

* Lateral effects, i.e., lateral or horizontal changes in resistivities of near-surface materials, can introduce errors in the inversion model and in some cases may result in fictitious layers in the model. Many times, lateral effects can be easily recognized on resistivity shifting of curve segments (for Schlumberger soundings) or graphical smoothing.

M--number of field readings

NN--number of fixed layer (model) parameters

RMSC--root-mean-square error cutoff value in percent
(typically use 1 to 5 percent).

Input No. 2A: IX (Input only for dipole-dipole array,
INDEX = 3)

IX--enter 0 if r is varied (n constant) or enter 1
if n is varied (r constant)

Input No. 2B: N

If IX = 0, enter one n-value

If IX = 1, enter M n-values

Input No. 3: INDX1

INDX1--enter 1 if field data are at perfectly logarithmic
electrode intervals, or enter 0 if otherwise

Input No. 3A: (SN(1), SN(2),SN(M))

SN(1)--electrode spacings, M-values. Skip if INDX1 = 1.

Input No. 4: R2(1), R2(2),R2(M)

R2(1)--field apparent resistivities, M-values, each
corresponding to SN(1)

Input No. 5: Model parameters (P(I), I = 1, 2E - 1)

Enter E-1 layer thicknesses, immediately followed by
E layer resistivities

Input No. 6: (NF(I), I = 1) NN)

NF(I)--fixed parameters. There should be a total of
NN numbers specifying which of the model
parameters in Input No. 5 are to be fixed. The
NF number assignment is consecutively from
NF = 1 for P(1) to NF = 2E - 1 for P(2E - 1).

23. Program execution will terminate when (a) the rms error drops below RMSC, (b) the program completes 15 iterations, (c) a minimum is reached before either (a) or (b) occurs and all further iterations increase the sum of squares (in this case, the note "J1 = JMAX--TRIAL MODEL will not converge," or (d) INDEX is set equal 0. The program will cycle to accept another set of data until INDEX = 0 is input.

Program output

24. Program output consists of printed listings of the results of the input initial model calculations (iteration No. 0) and computed

final model calculations and plots of field data, initial model, and final model. The output sequence and content is as follows:

- a. The results of iteration No. 0 are printed; these consist of a tabular listing of the input initial model parameters, tabular listing of electrode spacing, computed model apparent resistivity, and field apparent resistivity, and finally the rms error.
- b. A plot of the sounding curve for the input initial model is now generated (see Appendix B for plot specification input sequence).
- c. An optional plot of the field sounding curve can now be generated superimposed on the plot in b.
- d. The results of the final iteration are printed (including final rms error).
- e. A plot of the sounding curve for the final (best-fit) model is generated, which can be superimposed on the plots in b and c.

Examples

25. Example 1. In order to illustrate the input parameter sequence and the capability of RESINV to converge to a known model, the sounding curve corresponding to case 1 in Figure 8 was digitized and the resulting apparent resistivity versus L-spacing data were input to RESINV. The apparent resistivity values for 12 selected electrode spacings (from 6 to 400 m) were estimated directly from the log-log plot, so the input data would have "noise" due to errors in estimating values from the plot. An initial three-layer model was deduced from the general features of the sounding curve in Figure 8 and input to RESINV. Results of the use of RESINV to find a best-fit, three-layer model to the input data are shown in Figure 9 as Case I; the known model and the initial model are also shown. The best-fit, three-layer model labeled Case II in Figure 9 is the result of inputting the exact equally spaced (logarithmically) output data from RESDIR corresponding to Figure 8, using the same initial model as in Case I. For Case II, the program converges exactly to the known model; and for Case I, the final model is acceptable, with the greatest discrepancies for the second layer parameters. Figure 10 shows the input data and tabular output for Case I, and Figure 11 shows the plotted output (field data sounding curve and sounding curve and sounding curves for the initial and best-fit models).

<u>Known Model</u>	<u>Initial Model Used for Input to RESINV</u>	<u>Case I RESINV Best Fit Model (8 Iterations*)</u>	<u>Case II RESINV Best Fit Model (7 Iterations**)</u>
$h_1 = 10.00$		$h_1 = 9.88$	$h_1 = 10.00$
$\rho_1 = 1000.00$		$\rho_1 = 980.94$	$\rho_1 = 1000.00$
<hr/>	$h_1 = 20.00$	<hr/>	<hr/>
$h_2 = 10.00$	$\rho_1 = 1000.00$	$h_2 = 13.49$	$h_2 = 10.02$
$\rho_2 = 100.00$		$\rho_2 = 135.56$	$\rho_2 = 100.15$
<hr/>	<hr/>	<hr/>	<hr/>
$\rho_3 = 2000.00$		$\rho_3 = 1899.98$	$\rho_3 = 2000.00$
	$h_2 = 30.00$		
	$\rho_2 = 300.00$		
	<hr/>		
	$\rho_3 = 1500.00$		

* RMS error = 1.026; model began to diverge with 9th iteration
 ** RMS error = 0.002

Figure 9. Demonstration of ability of RESINV to converge to a known three-layer model from an initial model guessed from qualitative features of the sounding curve (calculated with RESDIR); Case I - arbitrarily spaced data with errors and Case II - equal logarithmically spaced exact data

```

=1
=6, 3, 12, 0, 1
=0
=6, 8, 10, 20, 30, 40, 60, 80, 100, 200, 300, 400
=950, 900, 870, 560, 400, 370, 440, 550, 650, 1020, 1200, 1300
=20, 30, 1000, 300, 1500

```

RESISTIVITY INVERSION PROGRAM

SCHLUMBERGER ARRAY

ITERATION NO. 0

LAYER NO.	THICKNESS	RESISTIVITY	THICK*RES	THICK/RES
1	20.00	1000.000	♦♦♦♦♦♦♦♦	0.020
2	30.00	300.000	9000.000	0.100
3		1500.000		

SPACING	MODEL RHO	FIELD RHO
6.000	996.882	950.000
8.807	990.498	889.033
12.927	972.381	783.348
18.974	926.422	587.184
27.850	831.707	420.305
40.878	694.559	370.628
60.000	586.079	440.000
88.068	588.822	591.563
129.266	698.780	783.237
189.737	855.054	992.875
278.495	1017.511	1170.905

RMS ERROR = 45.605

ITERATION NO. 8

LAYER NO.	THICKNESS	RESISTIVITY	THICK*RES	THICK/RES
1	9.88	980.942	9690.678	0.010
2	13.49	135.556	1828.021	0.099
3		1899.991		

SPACING	MODEL RHO	FIELD RHO
6.000	948.888	950.000
8.807	893.997	889.033
12.927	775.896	783.348
18.974	591.555	587.184
27.850	419.617	420.305
40.878	363.763	370.628
60.000	447.038	440.000
88.068	592.626	591.563
129.266	773.012	783.237
189.737	976.919	992.875
278.495	1189.910	1170.905

RMS ERROR = 1.026

Figure 10. RESINV input data and tabular output for Case I, Figure 9 (User input indicated by '=' sign.)

26. Example 2. Figure 12 is a plot of data from a Schlumberger sounding at a site about 8 km northwest of Vicksburg, Miss.* Qualitative evidence for as many as four layers can be seen in the sounding curve. An initial model, deduced from the sounding curve, for input to RESINV is also shown in Figure 12. Results of the inversion by RESINV are shown in Figure 13, where the sounding curve for the best-fit model (also illustrated in the figure) is indistinguishable from the field data.

27. The sequence of resistivities in the model shown in Figure 13 is geologically reasonable for the site: Layer 1 - sand fill; Layer 2 - saturated silts, sands, and clays with organic material; Layer 3 - freshwater sands and gravels; Layer 4 - Yazoo clay. Depth to the top of Layer 4 (~90 m), however, seems too large, since depths of 60 to 70 m are typical, although the depths are highly variable.

RESDAT: A General Purpose Resistivity
Data Processing Program

28. RESDAT is a general purpose computer program for processing resistivity field data. The basic function of the program is to take raw resistivity field data and process the data using Equation 1 to produce tabular and plotted output of resistivity as a function of profile position or electrode spacing for horizontal profiling or vertical sounding, respectively. Data from the following survey types can be accommodated: Wenner profiling, Wenner sounding, Schlumberger profiling, Schlumberger sounding, and pole-dipole surveying. In the case of Wenner and Schlumberger sounding data, an option is available to directly access a subroutine version of RESINV to interpret the data in terms of a resistivity model. For Wenner sounding data, options are available for producing cumulative sum (Moore, 1945) and/or inverse resistivity (Sanker Narayan and Ramanujachary, 1967) plots.

Input data

29. All data are input in free-field format. A program listing for RESDAT is given in Appendix D. If field resistance data ($\Delta V/I$) are

* Figure 12 was produced by the use of RESDAT to process the field data. RESDAT is discussed in the next section of this Part.

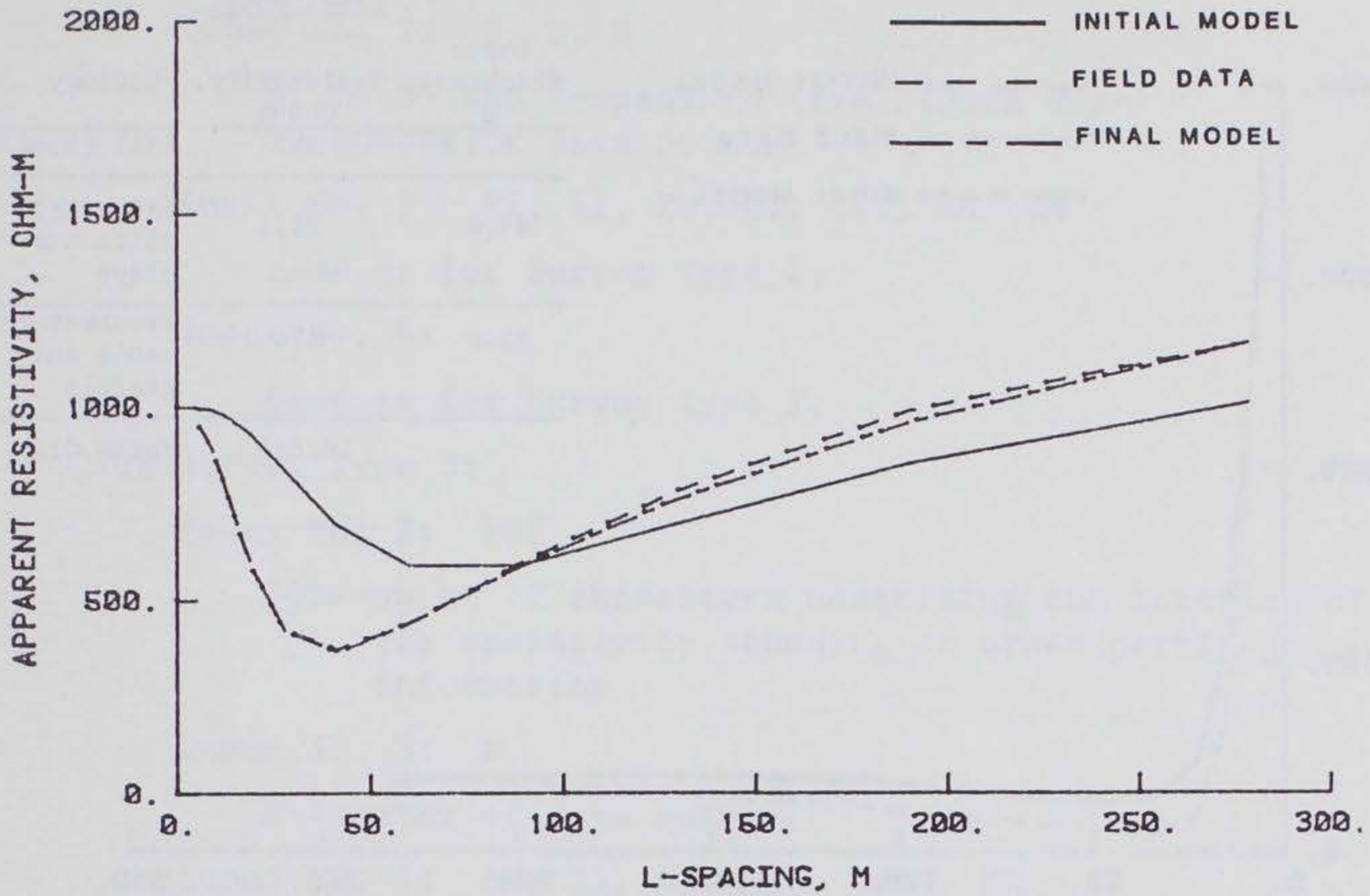


Figure 11. RESINV sounding curves (initial model, field data, and final model) for Case I in Figure 9

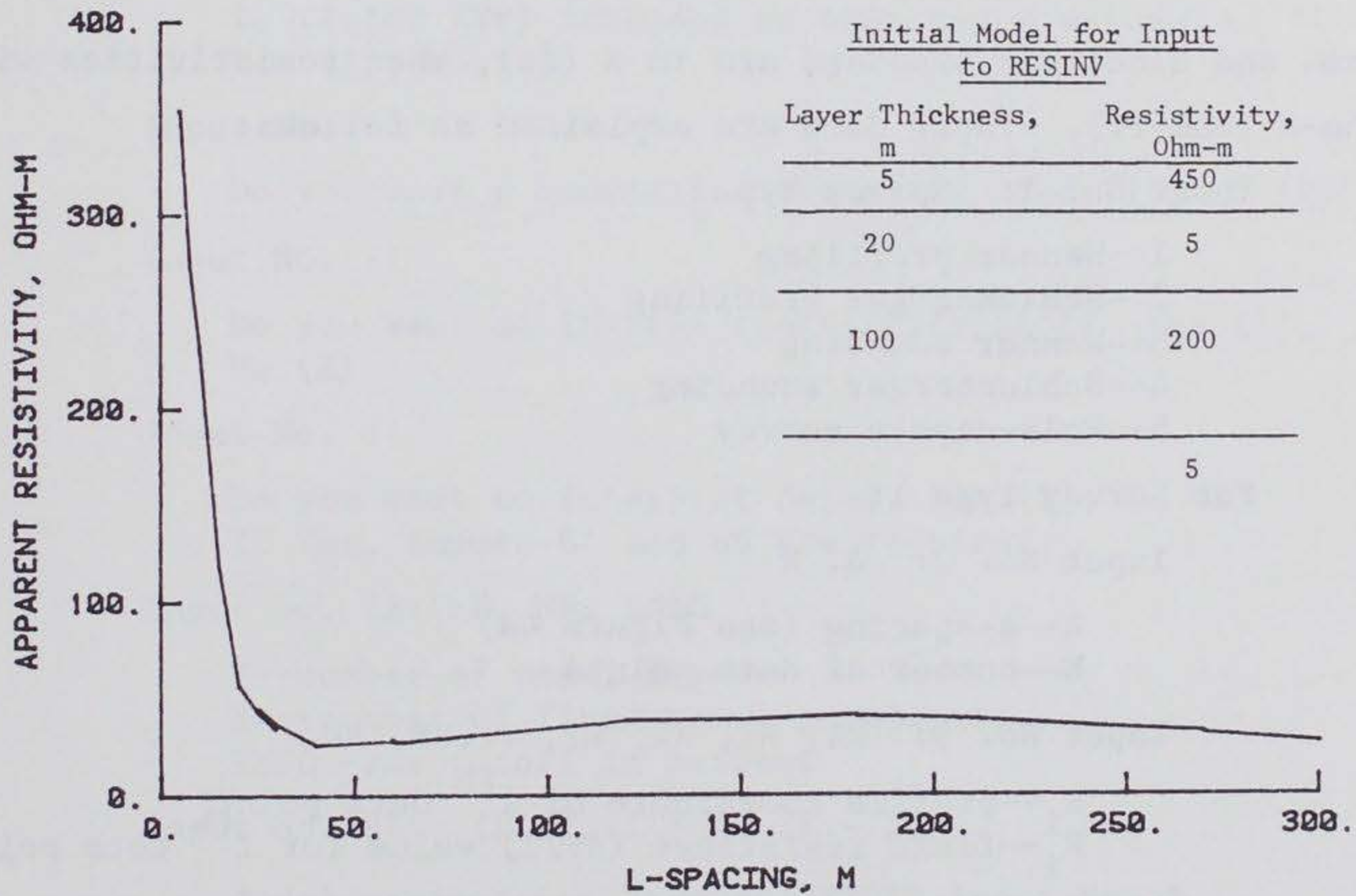


Figure 12. Schlumberger sounding curve obtained at site near Vicksburg, Miss.

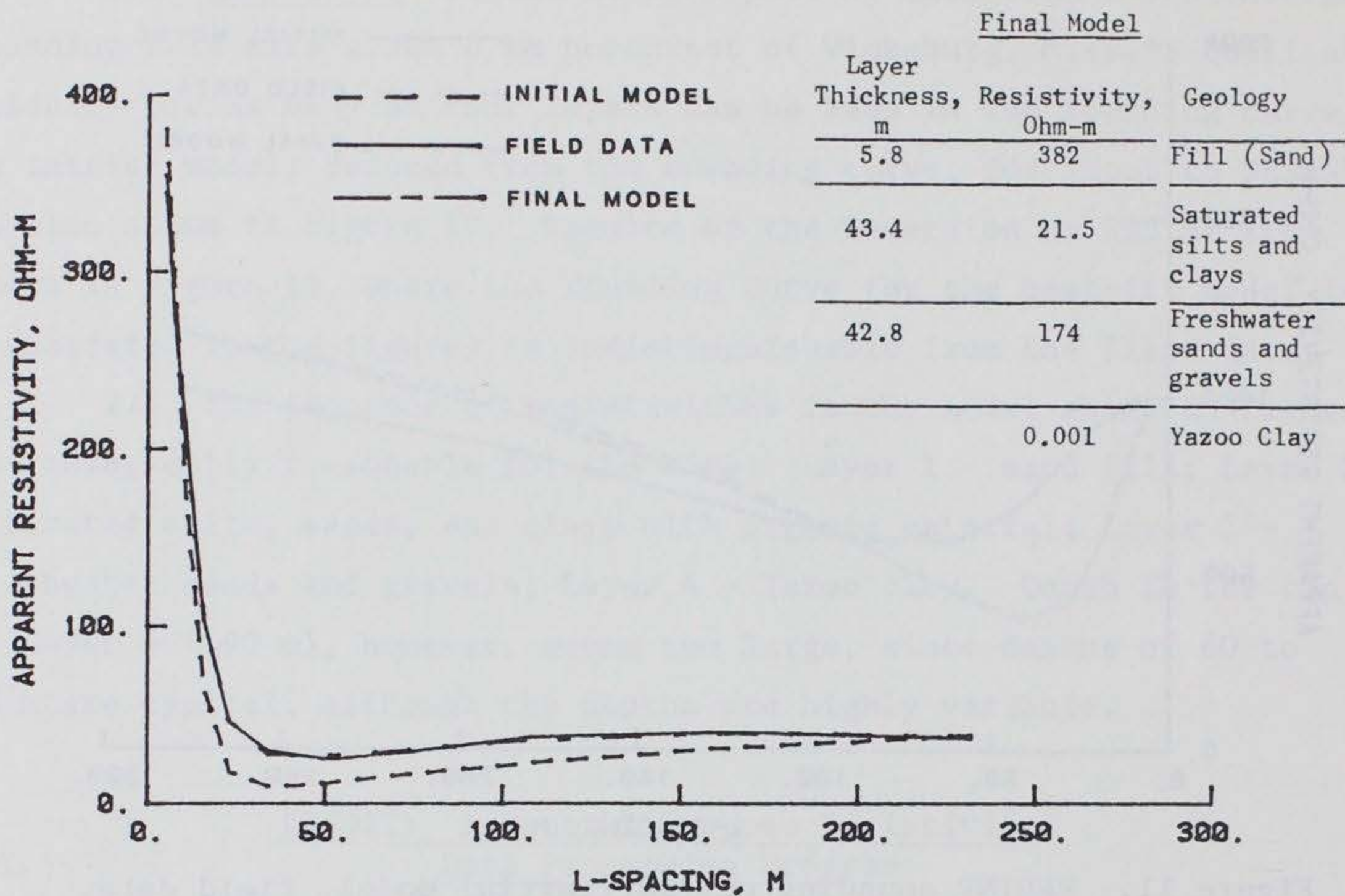


Figure 13. Results of RESINV inversion of field sounding curve and initial model shown in Figure 12

in ohms and electrode spacings are in m (ft), then resistivities will be in ohm-m (ohm-ft). Input data are explained as follows:

Input No. 1: Survey Type

- 1--Wenner profiling
- 2--Schlumberger profiling
- 3--Wenner sounding
- 4--Schlumberger sounding
- 5--Pole-dipole survey

For Survey Type 1:

Input No. 2: A, N

- A--a-spacing (see Figure 4a)
- N--number of data points

Input No. 3: X1, R1, X2, R2, ...SN, RN

- X_i--profile coordinate of ith data point
- R_i--field resistance ($\Delta V/I$) value for ith data point

Input No. 4:

- Is factor (2π) included in field resistance data?
- Type 1 for yes and 2 for no.

For Survey Type 2:

Input No. 2: S, L, N

S, L--S- and L-spacings (see Figure 4b)
N--number of data points

Input No. 3: X1, R1, X2, R2, ..., XN, RN

Same as for Survey Type 1.

Input No. 4:

Same as for Survey Type 1.

For Survey Type 3:

Input No. 2: POS

POS--up to 72 characters describing the location of
the resistivity sounding or other pertinent
information

Input No. 3: N

N--number of data points

Input No. 4: A1, R1, A2, R2, ...AN, RN

A_i --a-spacing for the i^{th} data point
 R_i --field resistance value for the i^{th} data point

Input No. 5:

Is factor (2π) included in resistance values?
Yes (1), No (2)

Input No. 6:

Do you want a cumulative sum plot? Yes (1), No (2)

Input No. 7:

Do you want an inverse resistivity plot? Yes (1),
No (2)

Input No. 8:

Do you want to interpret data? Yes (1), No (2)
If Yes, inputs 8A and 8B are required.

Input No. 8A: E, NN, RMSC

E--number of model layers
NN--number of fixed model parameters
RMSC--rms cutoff in percent

Input No. 8B: (P(I), I = 1, 2E - 1)

Model parameters; same as RESDIR Input No. 3.

For Survey Type 4:

Input No. 2: POS

Same as for Survey Type 3

Input No. 3:

Is factor (2π) included in field resistance values?
Yes (1), No (2)

Input No. 4: N

N--number of data points

Input No. 5: S1, L1, R1, S2, L2, R2, ...SN, LN, RN

S_i , L_i --S- and L-spacing for i^{th} data point

R_i --field resistance value for the i^{th} data point

Input No. 6:

Do you want to interpret data? Yes (1), No (2)
If yes, inputs 6A and 6B are required.

Input No. 6A: E, NN, RMSC

Same as for input No. 8A, Survey Type 3.

Input No. 6B: (P(I), I = 1, 2E - 1)

Model parameters; same as RESDIR Input No. 3.

For Survey Type 5:

Input No. 2: POS

POS--up to 72 characters describing the pole-dipole
current electrode station location and profile
direction information

Input No. 3:

Is factor (2π) included in field resistance values?
Yes (1), No (2)

Input No. 4: PP, N

PP--potential electrode spacing P_1P_2 (see Figure 4c)
N--number of data points

Input No. 5: CP1, R1, CP2, R2, ...CPN, RN

CP_i --distance from current electrode to first potential
electrode C_1P_1 (see Figure 4c) for i^{th} data
point

R_i --field resistance value for i^{th} data point

For all five survey types, an option is available, at the end of the
output sequence described below, to repeat the input sequence for
another data set of the same survey type.

Program output

30. The output of RESDAT will vary depending on survey type as listed below:

- a. Survey Type 1: Wenner Profiling Survey
 - (1) Tabular listing of profile position and apparent resistivity
 - (2) Plot of apparent resistivity versus profile position
- b. Survey Type 2: Schlumberger Profiling Survey
 - (1) Tabular listing of profile position and apparent resistivity
 - (2) Plot of apparent resistivity versus profile position
- c. Survey Type 3: Wenner Sounding
 - (1) Tabular listing of a-spacing and apparent resistivity
 - (2) Plot of apparent resistivity versus a-spacing sounding curve, either linear or log-log
 - (3) Optional plots of cumulative resistivity sum and/or inverse resistivity versus a-spacing plots
 - (4) If data interpretation is elected, all the output described for RESINV will follow
- d. Survey Type 4: Schlumberger Sounding
 - (1) Tabular listing of a-spacing, L-spacing, and apparent resistivity
 - (2) Plot of apparent resistivity versus L-spacing, either linear or log-log
 - (3) If data interpretation is elected, all the output described for RESINV will follow
- e. Survey Type 5: Pole-Dipole Survey
 - (1) Tabular listing of C_1P_1 , C_1P_2 , and apparent resistivity
 - (2) Plot of apparent resistivity versus X , where $X = (C_1P_1 + C_1P_2)/2$, i.e., each value of apparent resistivity is plotted at the profile location which is the midpoint of the potential electrode locations

Examples

31. Example 1. Figure 12 is an example of the use of RESDAT to process and plot field data from a Schlumberger sounding.

32. Example 2. A large portion of the Medford Cave site (see Figure 1) was surveyed by resistivity profiling, using the Wenner array

with $a = 40 \text{ ft}^*$ and 10-ft station spacing along the profile lines. A plot of apparent resistivity for $a = 40 \text{ ft}$ for one profile line at the Medford Cave site is shown in Figure 14 (apparent resistivity for $a = 10 \text{ ft}$ is also shown along the same profile line). Apparent resistivity for all the profile lines was input to the general purpose

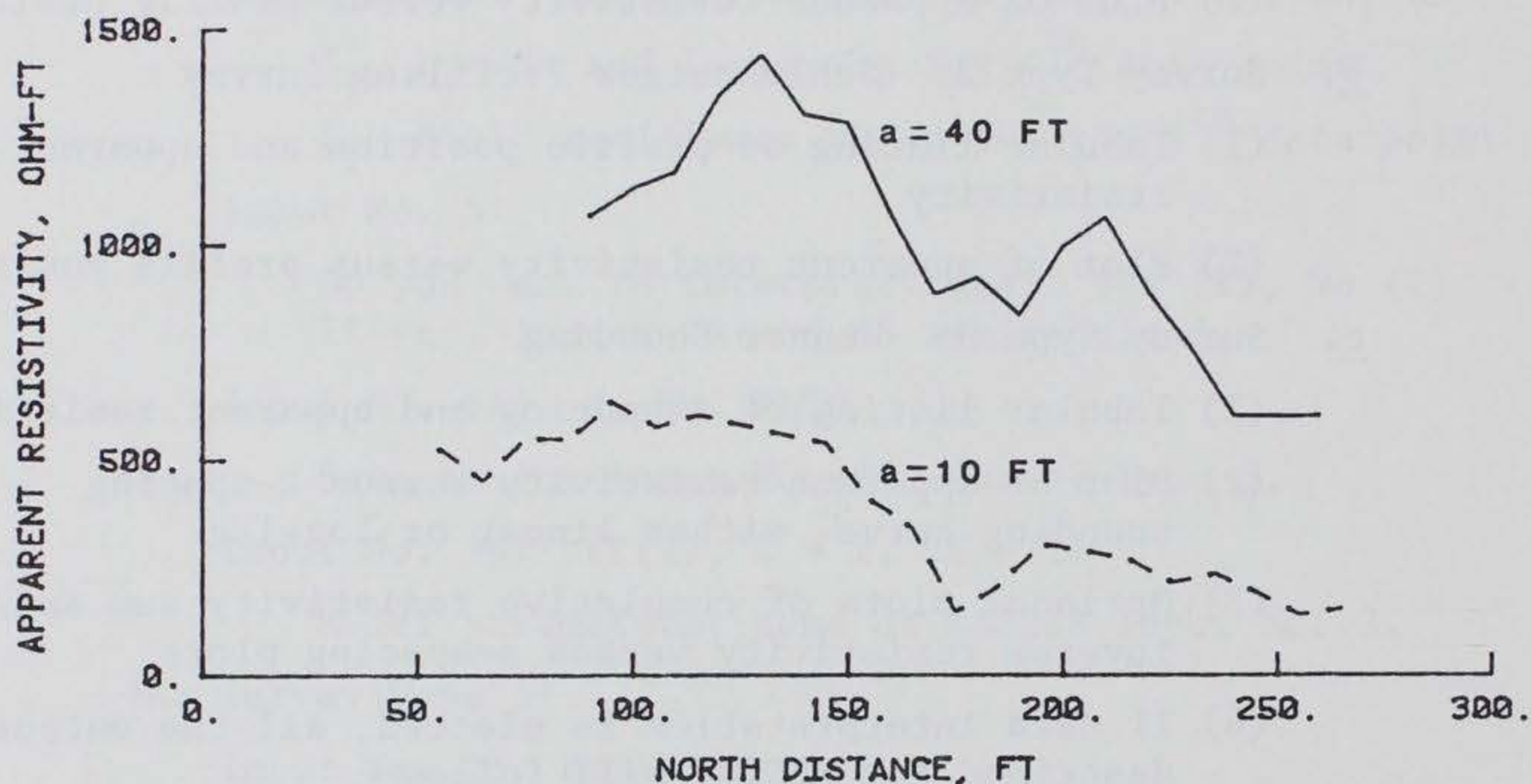


Figure 14. Two horizontal resistivity profiles along the (0,80) to (260,80) line at the Medford Cave Test site (see Figure 2)

contouring program CONTOUR (Tracy, 1974) to produce the apparent resistivity contour map shown superimposed in Figure 15. A plan map of the known cavity system at the site is shown superimposed in Figure 15. An a-spacing of 40 ft was chosen so that the depth of investigation of the resistivity survey would be sufficient to include the effects of the known cavity system. The apparent resistivity contour map is significantly affected by and reflects the presence of the cavity system. Since the "normal background" resistivity is apparently 400 to 600 ohm-ft, the cavity system is responsible for a resistivity anomaly of about 1000 ohm-ft, although the shape of the resistivity contours does not closely match the cavity shape.

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

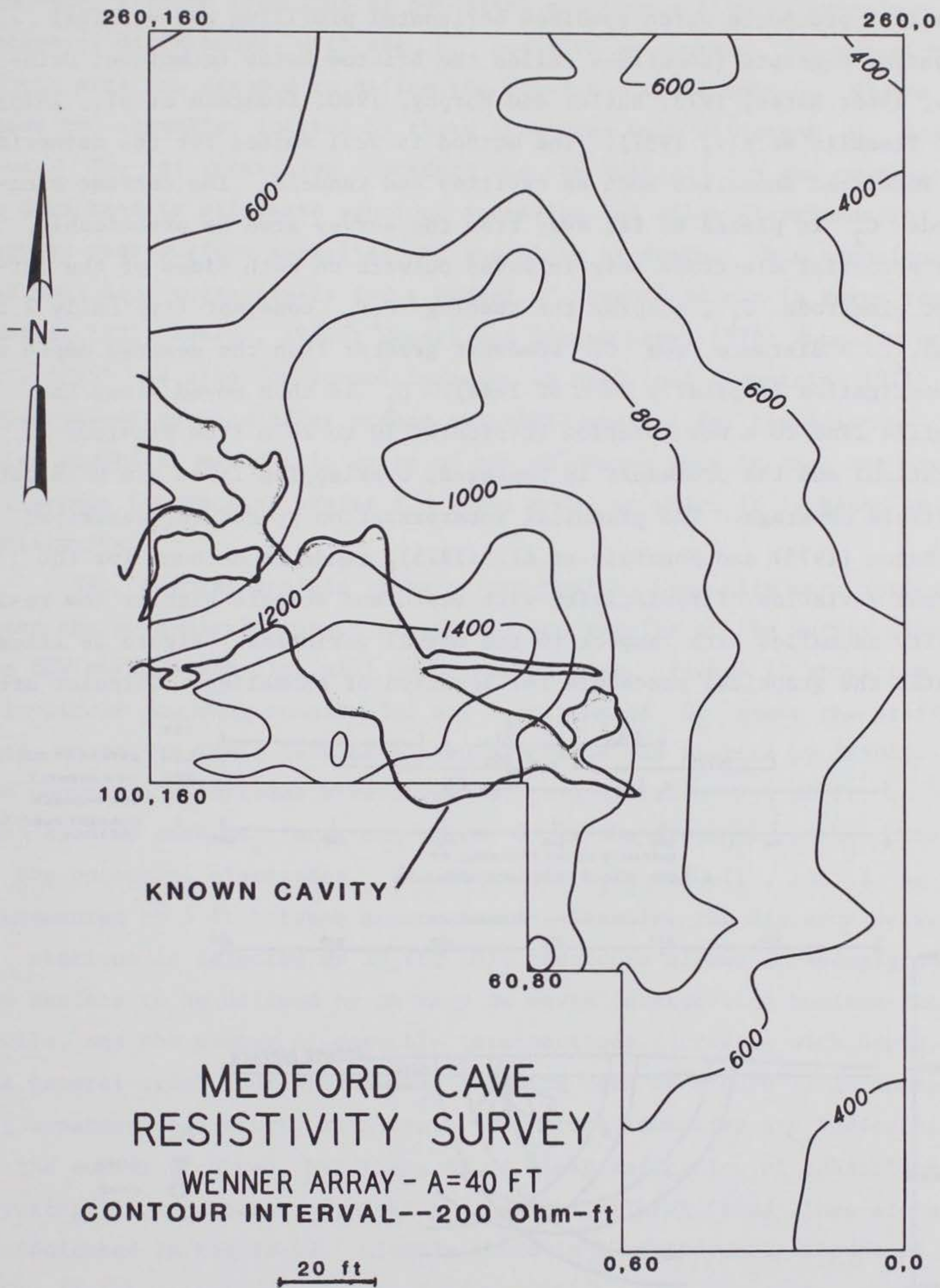


Figure 15. Resistivity contour map for a portion of the Medford Cave site, Wenner electrode array with 40-ft electrode spacing

33. Example 3. The pole-dipole array (Figure 4c) can be used in a survey procedure which combines horizontal profiling and vertical sounding concepts (sometimes called the Bristow-Bates technique; Bristow, 1966; Bates, 1973; Butler and Murphy, 1980; Fountain et al., 1975; and Franklin et al., 1981). The method is well suited for the detection of localized anomalies such as cavities and tunnels. The current electrode C_2 is placed as far away from the survey area as practicable. The potential electrode pair is moved outward on both sides of the current electrode C_1 , keeping the spacing P_1P_2 constant (typically 2 to 3 m), to a distance from C_1 somewhat greater than the desired depth of investigation (typically 50 m or less). C_1 is then moved along the profile line to a new location (typically 10 to 20 m from previous location) and the procedure is repeated; overlapping lines are used for multiple coverage. The graphical interpretation procedure, described by Bates (1973) and Fountain et al. (1975), tends to account for the normal variation of resistivity with depth and selects high or low resistivity anomalies with respect to the normal variation. Figure 16 illustrates the graphical procedure for location of anomalies. Circular arcs

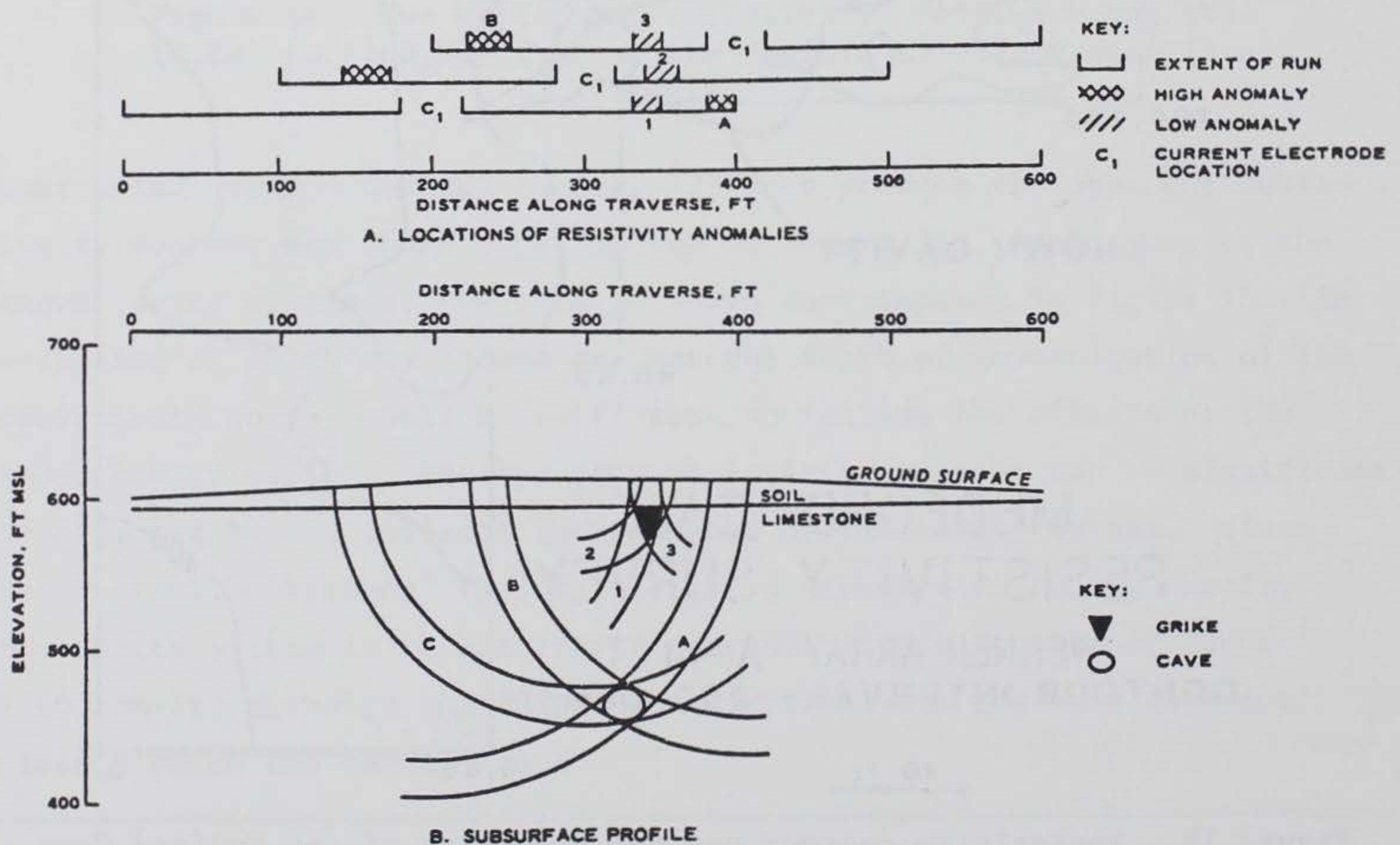


Figure 16. Simplified example of graphical interpretation of pole-dipole resistivity data for anomaly location (Bates, 1973)

are drawn through locations of potential electrodes showing anomalous potential differences, with the C_1 position as center. Intersections of the arcs are assumed to define the locations of anomalies. Figure 16 shows two anomalies located by three traverses with different C_1 locations. The interpretation procedure and the multiplicity and overlapping of data tend to eliminate spurious anomalies and allow discrimination between near-surface anomalies and anomalies at depth. This technique has been used successfully for a number of investigations in karst regions (Bates, 1973; Butler, 1980c; Cooper and Bieganousky, 1978; Fountain et al., 1975) and also for tunnel location in hard rock (Fountain, 1975). These investigations offer strong empirical support for the Bristow-Bates graphical method, in spite of the objection that it does not have a rigorous theoretical basis; i.e., the model on which it is based is qualitative.

34. Several profile lines at the Medford Cave site were surveyed using the pole-dipole survey procedure, and results of the survey along the 80W north-south line will be presented here. Figure 17 shows the pole-dipole sounding results for six locations of C_1 along the profile line, where the field data have been processed and plotted by RESDAT. The potential electrodes were moved out to a distance $X = 80$ ft on each side of each C_1 station, where X is the distance to the center of the potential electrodes. The distance $P_1P_2 = 10$ ft, and X is incremented by 5 ft between measurements. Finally, the distance between C_1 stations is selected as 30 ft; this procedure allows an anomaly near the surface to be defined by as many as seven intersecting hemispherical shells, and the number of possible intersections decreases with depth. The general trend indicated by the sounding data in Figure 17 is increasing apparent resistivity with depth. Numerous anomalies are indicated in the sounding curves, but there is no clear indication of subsurface layering. For purposes of picking anomalies, linear trend lines are used as indicated in Figure 17. Clearly there is a considerable amount of subjectivity in this procedure of picking high and low anomalies; success relies on (a) experience of the interpreter and (b) the considerable redundancy of the data. The results of an analysis of the complete

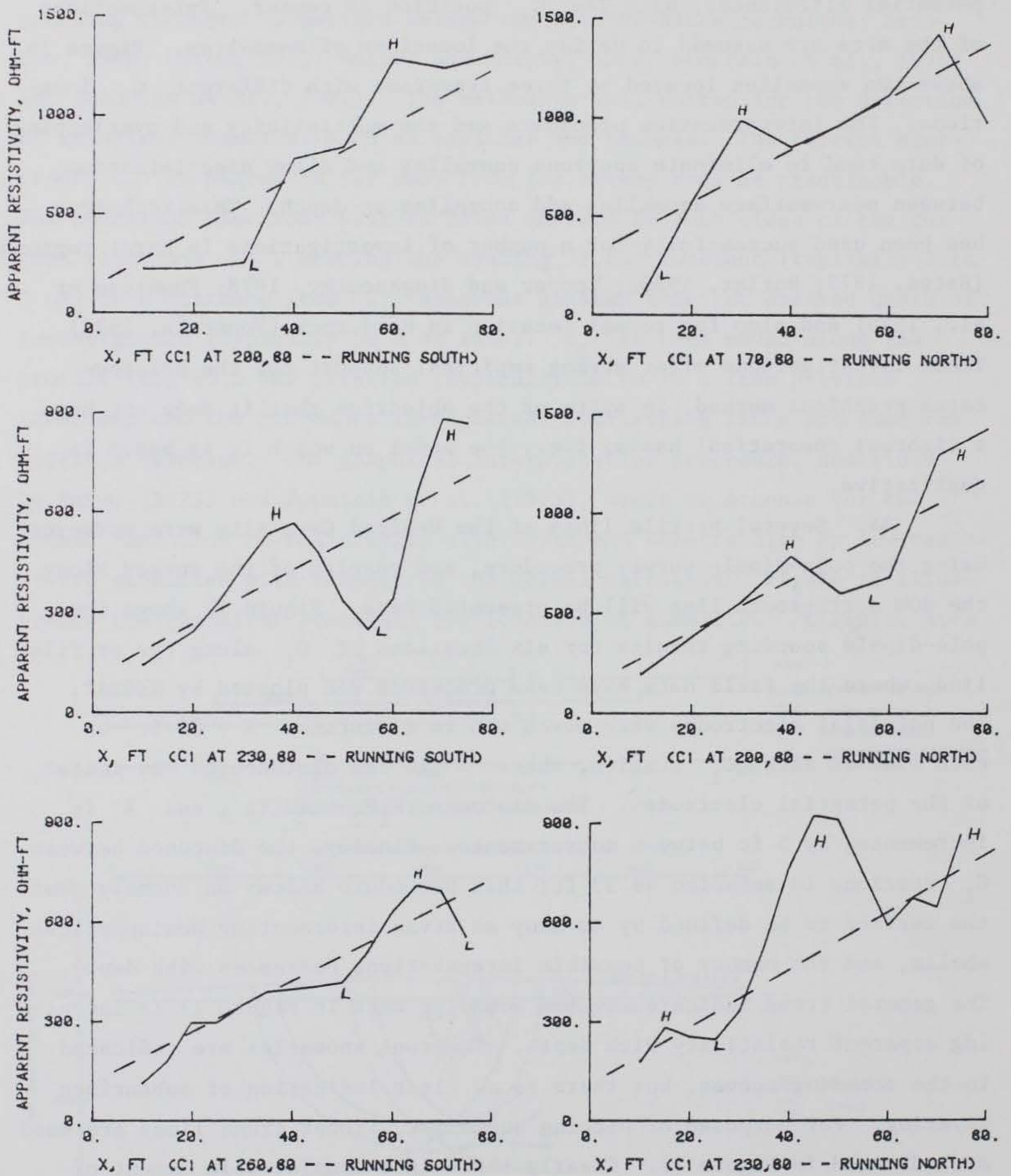


Figure 17. Six pole-dipole sounding curves at 30-ft spacing along the (0,80) to (260,80) line at the Medford cave site

profile line, using the techniques illustrated in Figure 16, are shown in Figure 18. The correlation of the resistivity anomalies with known geologic features (Butler, in press) is quite good.

35. A major drawback to the pole-dipole survey technique just presented is the time required to conduct the field tests and process and interpret the data. Use of RESDAT to process and plot the data is a considerable help, but there is still much which could be done to automate the procedures. An automated resistivity data acquisition system demonstrated by the Southwest Research Institute (SwRI) at the Medford Cave site appears to be a solution to the field time constraint (Fountain and Herzig, 1980). Data are recorded in a digital format with the SwRI system, which can then be processed by the graphical procedure presented here or by an automated interpretation procedure developed by SwRI (Fountain and Herzig, 1980; Spiegel et al., 1980). Although work on the automated technique is continuing at SwRI, currently the technique is limited by the assumption of a single anomaly in a uniform half-space; while the graphical procedure used in this report is subjective, it is not subject to these limitations. A technique which has been successfully utilized at WES for a specific data set is to digitize the locations of high and low anomalies along the profile line and then determine subsurface anomaly locations with an arc-intersection algorithm programmed on a minicomputer; this procedure has not yet been generalized.

POLE-DIPOLE RESISTIVITY ANOMALIES

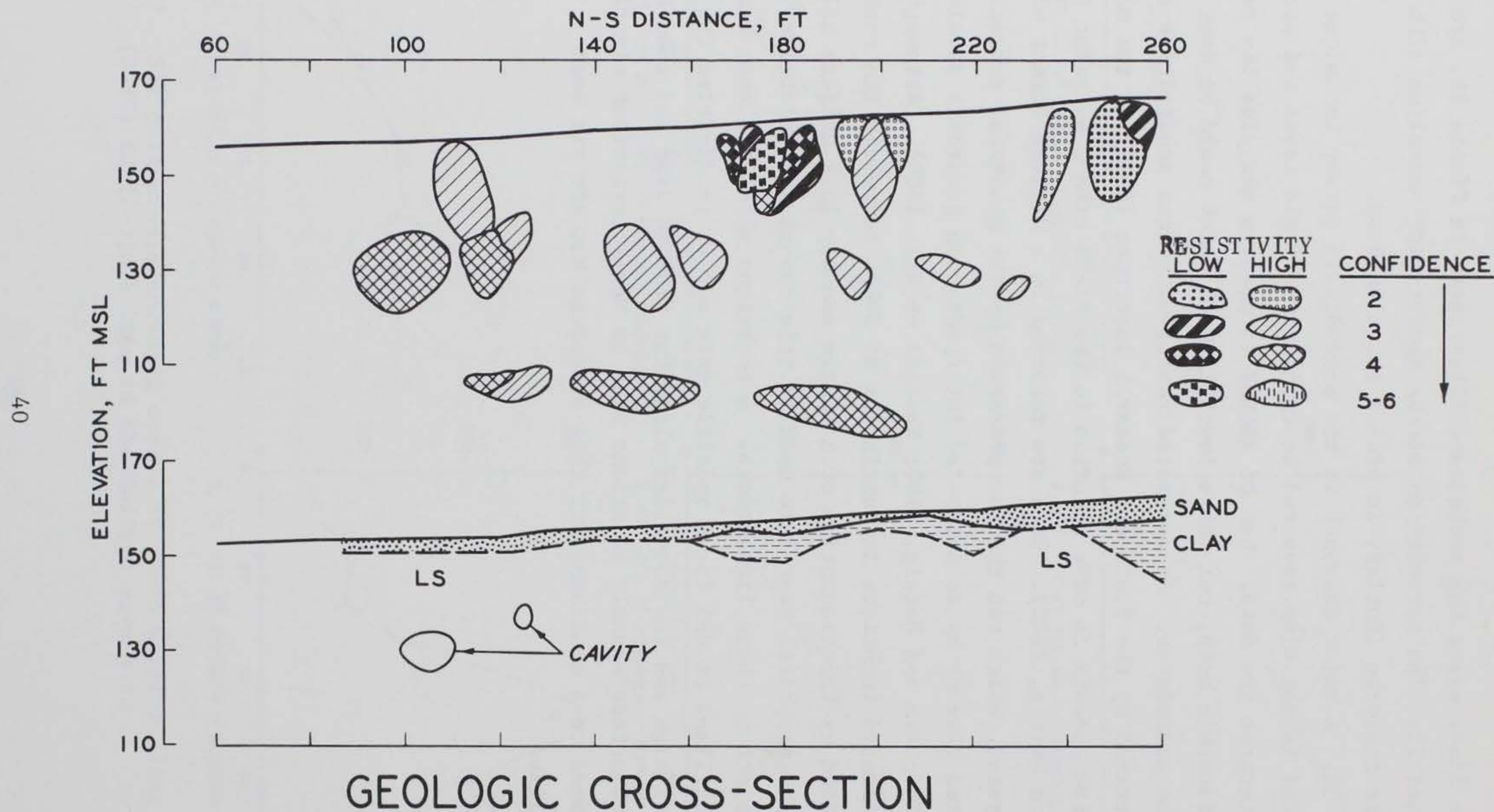


Figure 18. Interpreted pole-dipole resistivity cross section compared with known geology along the (0,80) to (260,80) line at the Medford Cave site (Numbers indicating increasing confidence levels correspond to the number of arc intersections which define the anomaly.)

PART III: MICROGRAVIMETRIC TECHNIQUES

Background

36. Microgravimetry is a geophysical method that offers special advantages over other subsurface exploration methods in a variety of applications. The term "microgravimetry" refers to geophysical investigations involving relative measurements of the acceleration of gravity that require measurement accuracy and precision and instrument sensitivity in the μGal range ($1 \mu\text{Gal} = 10^{-6} \text{ Gal} = 10^{-6} \text{ cm/sec}^2 \approx 10^{-9}$ times the earth's normal gravitational acceleration). For geophysical applications, delineation of features with characteristic dimensions of 1 m or less is often desirable, while the maximum depth of interest may typically be 100 m or less. Many attempts to apply gravimetry to geotechnical and shallow structural problems have been disappointing in that the anomalies due to small structures of interest could not be extracted from the data; i.e., only anomalies due to very large or very shallow structures (or some fortuitous combination of the two factors) could be resolved. However, with modern "microgal" gravity meters and refined field and interpretation procedures, microgravimetry is a viable geophysical tool for application to military facility foundation and perimeter security investigations (Butler, 1980a).

37. The gravity method involves the measurement of the vertical component of the gravitational attraction at the surface. The measurement or determination of the first vertical and horizontal derivatives (gradients) of the vertical component of the gravitational attraction can be of considerable fundamental and practical importance. Measurement of the gradients or determination of the gradients from gravity profiles offers two particular advantages over measurement of just gravity alone:

- a. The gradient profiles have diagnostic properties, that, in many cases, make subsurface structure identification more straightforward.
- b. The gradients selectively filter out the effects of deeper-seated structures and enhance anomalies caused by

shallow structures of interest in geotechnical investigations.

Butler (1980a, b, c) discusses the measurement and application of gravity gradients.

38. Field procedures, data processing, and interpretation techniques for microgravimetric surveys are discussed in detail in Butler (1980a, d, and in press) and Butler et al. (in press); only a brief outline of these procedures and techniques will be presented here. Microgravimetric field procedures can be summarized as follows:

- a. Establish survey grid or profile line and determine relative elevations at all grid stations.
- b. Establish gravity base station.
- c. Conduct gravity survey returning to the base station frequently (at least once per hour).
- d. Correct gravity data in a timely manner while in the field so that questionable data can be discovered and the associated station reoccupied for another gravity measurement and so that the density of gravity stations in areas of interest can be increased.

39. The sequence of corrections applied to gravity measurements is as follows:

- a. Correct for changes in gravity at the site as a function of time caused by earth-tide variations and gravity meter drift (drift correction).
- b. Correct for variations in north-south positions of gravity stations (latitude correction).
- c. Correction for elevation differences between stations (free-air and Bouguer corrections).
- d. Correct for topographic variations around each gravity station.
- e. Plot and contour the gravity data.

40. Although interpretation techniques vary greatly depending on the investigator as well as the objectives of the survey, the following will suffice for the present discussion:

- a. Separate regional gravity components in the data from the local components; this is called the regional-residual separation.

- b. Optionally generate processed gravity maps, such as derivative maps (Butler, in press) or upward/downward continuation maps (Grant and West, 1965).
- c. Identify gravity anomalies.
- d. Classify anomalies for qualitative interpretation or decide on a model for quantitative interpretation.
- e. For quantitative interpretation, determine parameters of the model.

41. Considering the procedures and techniques identified in microgravity data acquisition, processing, and interpretation, the following list identifies specific steps which could facilitate and/or improve the microgravity method:

- a. In item 37a, use of state-of-the-art electronic surveying systems for establishing survey grids and obtaining relative elevations could substantially reduce data reduction time for elevation surveys.
- b. Develop computer algorithms for generating gravity station occupation schemes for given survey area size and shape and base station location; these schemes should optimally randomize possible errors over the gravity stations occupied between base station reoccupations, minimize walking distances, and include a desired 20 percent station reoccupation rate.
- c. Develop computer programs for automatically correcting gravity data and producing Bouguer gravity contour maps.
- d. Develop automated techniques for making the regional-residual separation and plotting residual gravity maps.
- e. Develop automated techniques for generating processed gravity maps.
- f. Develop procedures for identifying and classifying anomalies.
- g. Develop efficient procedures for determining the parameters of structural models.

42. Only selected aspects of this "shopping list" can be addressed as part of the current effort; these aspects are briefly discussed, three computer programs developed as part of this effort are documented, and short selected examples of the use of the computer programs are presented. Finally, two more detailed examples will be presented which illustrate the use of the computer programs for processing and interpreting gravity data.

Gravity Station Occupation Schemes

43. In microgravity surveying, it is desirable to keep errors from all sources as low as possible; generally an accuracy of ± 5 μGal or better is desired in order that anomalies at the $10\text{-}\mu\text{Gal}$ level can be detected (Butler, 1980a). The manner or sequence in which gravity stations are occupied during a survey can greatly influence the accuracy and overall quality of a microgravity survey. All stations that are occupied between successive reoccupations of the base station are referred to as a program. Each program should be planned to allow a base station reoccupation in less than one hour and to include gravity station reoccupations at an average rate of about 20 percent. Since the average time for acquiring gravity measurements in a microgravity survey is about 5 min per station, a program generally will consist of ~ 10 gravity readings, of which typically eight readings would be "first-time" station occupations and two readings would be station reoccupations.

44. Programs should be designed to occupy stations in a "zigzag" or "leap-frog" fashion in order to distribute random errors and to prevent any cumulative errors from combining to produce fictitious anomalies or elongated anomalies such as can result from long, continuous programs of station occupations (Butler, 1980a).^{*} Figure 19 is a plan of the gravity stations for the Manatee Springs site microgravity survey, showing several typical programs. Clearly, the station occupation scheme shown in Figure 19 is not optimum, although errors will be properly randomized. An optimally generated occupation scheme should have approximately equal walking distances between each station in the program, including the base station at the beginning and end of a program. Optimal station occupation schemes are considered an important aspect of microgravity surveying, and work will continue toward finding expeditious manual or computer-aided methods for generating occupation schemes.

* Personal communication, 1979, R. Neumann, Compagnie Generale de Geophysique, Massy, France.

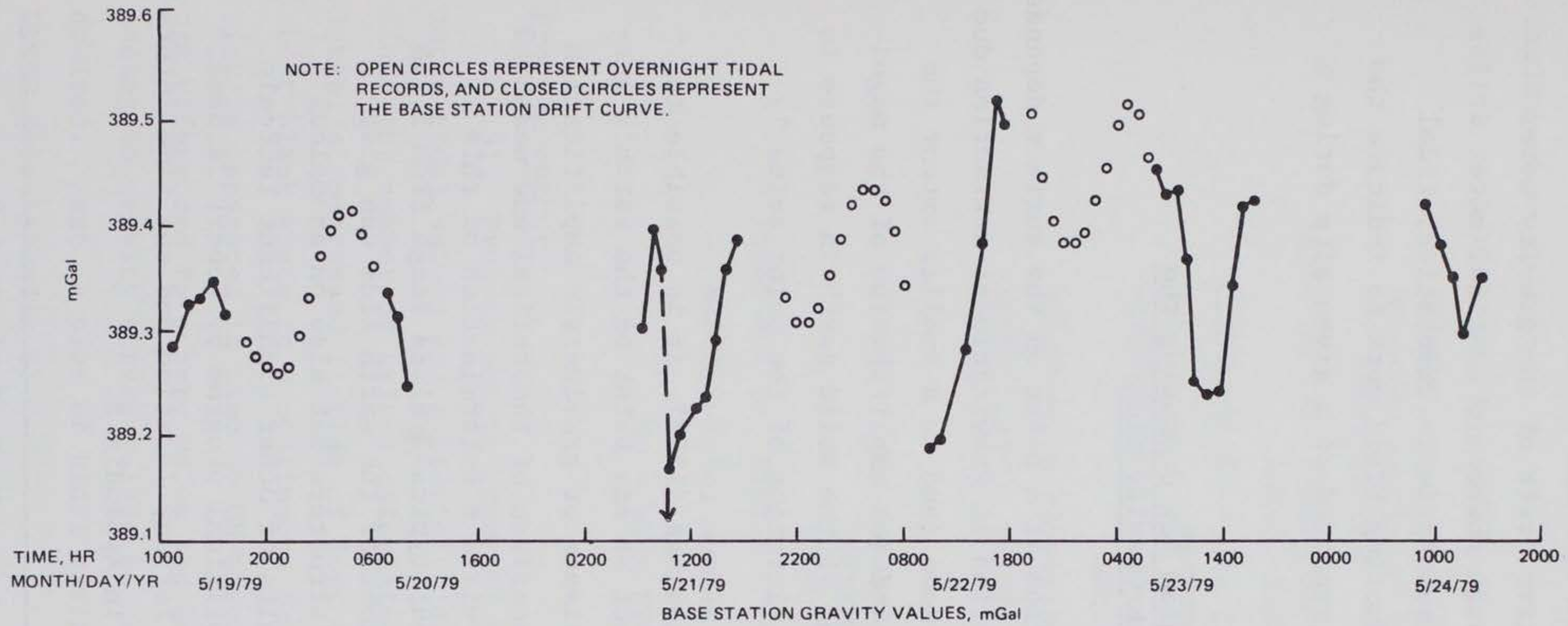
Use of Theoretical and Measured
Earth-Tide Records

45. Reoccupations of the base station during a microgravity survey are used to construct a survey drift curve. The drift curve, which includes components due to both earth tides and instrument drift, is used to correct measurement values at all stations in the survey grid for time variations of the gravity values. It is assumed that the time variation observed at the base station is the same at all stations. Generally, the drift curve will consist of the earth-tide component, which can actually be calculated theoretically for a given site, a long-term cumulative instrument drift component, and a noncumulative instrument "drift" component, which can be caused, for example, by "rough handling" of the gravity meter. Frequent base station reoccupations coupled with the use of theoretical and measured tidal curves can be of great value in assessing the magnitudes of these components of the drift curve, for assuring the consistency of gravimeter performance during the survey, and for improving the overall accuracy of microgravity surveys.

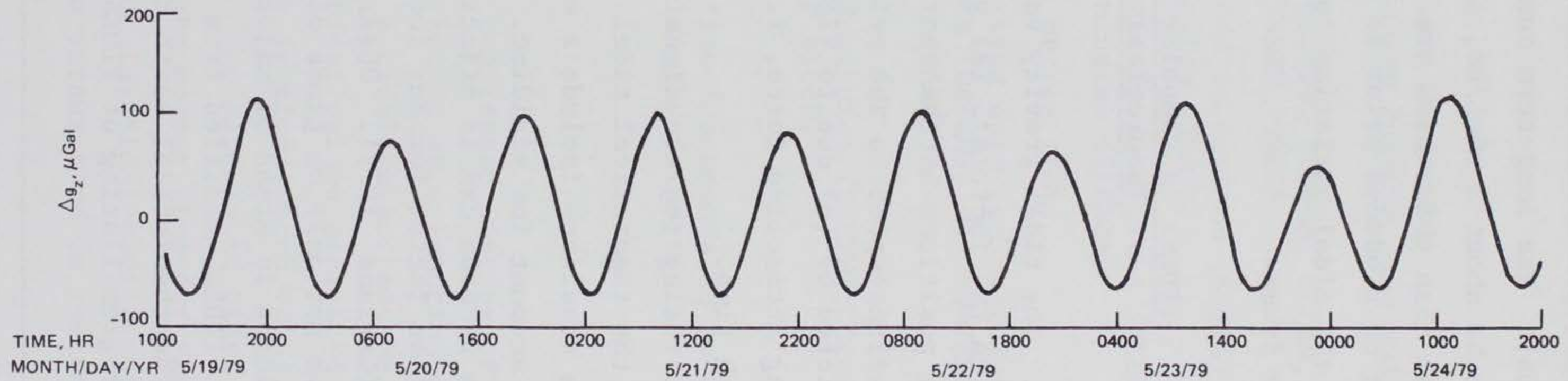
46. Figure 20 is an example of the use of measured and theoretical earth/gravity tide records in conjunction with the field drift curve for the microgravity survey at the Medford Cave site. Since the overnight tidal records were recorded in a different location (i.e., a local motel room), the segments have been shifted vertically to best fit the base station curve. The phase of the two sets of data agrees quite well, but the amplitude variations of the field curve are more extreme. The arrow marks a base station reading just after an accidental jolt to the gravity meter; because of the frequent base station reoccupations, the recovery period after the jolt is adequately defined.

47. The theoretical curve in Figure 20 was produced by the program TIDES, which is described later in this Part. There is approximately 17 a 4-hr phase difference between the theoretical and measured tidal curves; such phase differences are not uncommon.* Discounting the phase

* An example is given later in this Part of a case where the phase agreement is nearly exact.



a. BASE STATION DRIFT CURVE FOR PART OF SITE MICROGRAVITY SURVEY WITH OVERNIGHT TIDAL RECORDS



b. THEORETICAL EARTH TIDE FOR SITE

Figure 20. Field base station drift curve and theoretical and observed earth/gravity tide records for the Medford Cave site microgravity survey

shift, there is good agreement between the amplitudes of the measured tidal curve (open circles, Figure 20a) and the theoretical tidal curve (Figure 20b). The long-term cumulative drift of the gravity meter appears to be about 2 $\mu\text{Gal/hr}$, although there are nontidal meter drifts much larger than this which are not cumulative. Theoretical tidal curves can be produced prior to conducting field work to indicate the nature of the tidal variation to be expected at a given site during a given time frame.

TIDES: A Computer Program for Computing the
Theoretical Earth Gravity Tide

48. The tidal gravity variation at a point on the surface depends primarily on two factors: (a) variation in gravitational attraction due to varying positions on the sun and moon (and to a smaller extent the planets) with respect to the point; and (b) amplification of the magnitude predicted by (a) due to yielding of the solid earth in response to the varying attractive force, i.e., elevation of the point actually varies with time.

49. Using the equations of Longman (1959), it is possible to calculate the theoretical tidal effect at any point on the earth's surface. The equations include a compliance or gravimetric amplification factor to account for yielding. Comparison of theoretical and measured earth tide records can in principle yield a determination of this amplification factor for any location; typical values range from 1.138 to 1.240 (Garland, 1977). Observations of the earth tide can give information not only on gross earth structure but also on anomalous tidal yielding in areas of major faults or other significant tectonic features. TIDES, modified from an original program by Robert Jachens,* computes the theoretical earth tide for any location and any time interval. A program listing of TIDES is in Appendix E.

* Personal communication, Robert Jachens, U. S. Geological Survey, Menlo Park, Calif.

Input data

50. All data are input in free-field format. Data input are explained as follows:

Input No. 1: NCOMP, MM

NCOMP--number of tidal input data sets

MM--time increment in minutes between tide value calculations

Input No. 2: SLATD, SLATM, SLONGD, SLONGM, SELEV, DATEM, DATED, DATEY, TIMEH, TIMEM

SLATD, SLATM--site latitude in degrees (SLATD) and decimal minutes (SLATM)

SLONGD, SLONGM--site longitude in degrees (SLONGD) and decimal minutes (SLONGM)

SELEV--site elevation in metres (MSL)

DATEM, DATED, DATEY--starting date for calculation in month (DATEM), day (DATED), and year (DATEY) form

TIMEH, TIMEM--starting time for calculation in hours (TIMEH) and minutes (TIMEM), Greenwich time (24-hr clock)

Input No. 3: NTOTAL

NTOTAL--total number of time increments to be calculated, i.e., the total length of the tidal record will be = MM x NTOTAL

Program output

51. Program output consists of a compressed listing of calculated tidal values and a plot of tide variation as a function of time. Since the number of values calculated in a tidal record may be very large, a compressed listing of just the tidal values separated by a short blank space in a continuous fashion is given; each value in the list is separated in time by MM-minutes. The calculated tidal values are referenced to a zero value and have the proper sign for algebraically adding to gravity survey values to correct for tidal variations if desired. Next, a plot of tidal variation versus time is generated using PLOT2 (see Appendix B).

Example

52. An example output plot from TIDES has already been discussed (Figure 20). As another example, Figure 21 compares theoretical and observed earth tides for Vicksburg, Miss., for a three-day period (16-18 May 1980). The phases of the two curves in Figure 21 agree quite well. Amplitudes of the minima and secondary maxima of the two curves agree closely; however, the primary maxima of the measured tidal curve are nominally 50 μGal larger than the corresponding maxima on the theoretical curve. There are two possible explanations for the amplitude differences: (a) a small portion of the amplitude difference could be due to using a compliance factor that is too small for the site (1.160 was used); and (b) the electronic output of the gravimeter is nonlinear relative to the null position (McConnell, Hearty, and Winter, 1974). Since the position of the tidal variation relative to the meter null position will vary because of the superimposed approximately 2 $\mu\text{Gal/hr}$ drift, the gravimeter tidal curve would require frequent nonlinearity calibrations if used for quantitative tidal variation studies. The vertical scale of the measured curve was generated about the actual output position at 1930 hr on 18 May. At this time, drift has carried the tidal variation curve to within about 120 μGal of saturation of the electronic output on one side of the null position. The three events superimposed on the tidal record on 18 May in Figure 21 are earthquakes and illustrate an interesting application of the microgravimeter as a long-period vertical seismometer. Monitoring gravimeter tidal variation overnight during field surveys for the occurrence of large earthquakes will alert field parties as to the source of larger than normal background noise, since large earthquakes will produce noise levels as large as 100 to 200 μGals over a several hour period (Butler, 1980a).

Polynomial Surface-Fitting for Regional-Residual Separation

53. A polynomial surface-fitting procedure for determining regional fields is presented by Coons, Wooland, and Hershey (1967) for large-scale gravity surveys. This procedure was applied to the Manatee

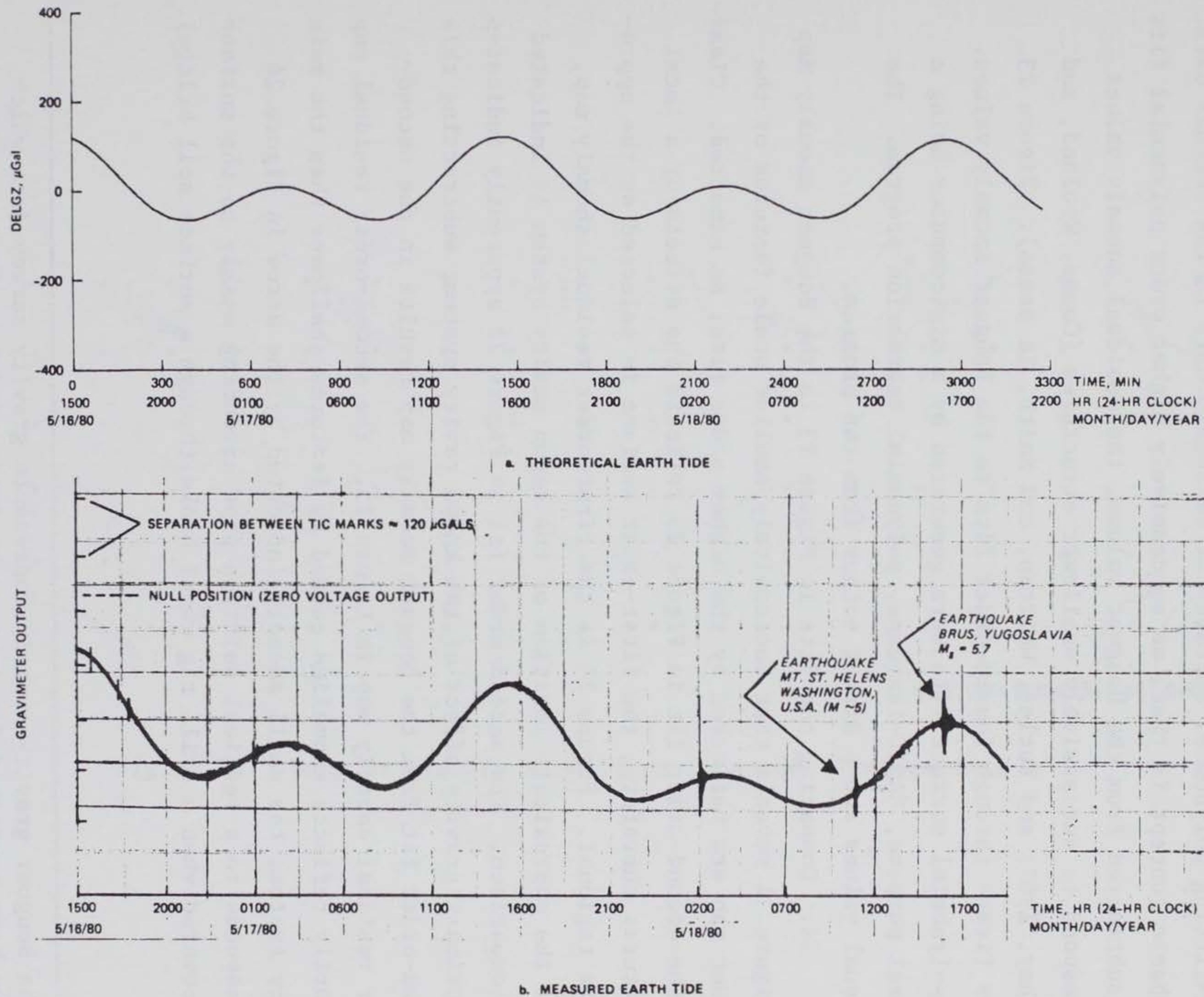


Figure 21. Comparison of theoretical earth tide and earth tide measured with Model-D gravimeter at Vicksburg, Miss., for three-day period

Springs microgravity survey data in order to determine its applicability to small-scale surveys. Figure 22 is a Bouguer anomaly (Butler, 1980a)* contour map for the survey. The surface-fitting procedure determines best-fitting polynomial surfaces of various orders to the Bouguer data. The basic concept is that, as successively higher order polynomial fits are subtracted from the Bouguer values, the residual anomaly values correspond to successively shallower structures (Coons, Wooland, and Hershey, 1967; and Butler, Whitten, and Smith, in press). Figure 23 shows first- through fourth-order fits to the Bouguer anomaly values. The polynomial surface fits were generated by a minicomputer using a general purpose, BASIC-language, polynomial regression program. The residual values are a direct output from the program.

54. Comparing the fits in Figure 23 to the Bouguer anomaly map in Figure 21 reveals that successively smaller scale features of the Bouguer map are reflected by the higher order fits, as expected. Clearly, the second-order fit in Figure 23 reflects the effects of a local structure; therefore, the first-order surface is selected as the appropriate regional. Figure 24 is the first-order residual anomaly map, where the approximate location of the known cavity system is indicated for comparison. The second-order fit in Figure 23 apparently indicates the primary gravity effect of the known cavity system; subtracting this second-order fit from the Bouguer anomaly map results in the second-order residual anomaly map in Figure 25. The second-order residual map primarily reflects anomalies caused by features shallower than the main cavity system; the small anomaly indicated by the arrow in Figure 24 corresponds to a vertical solution pipe extending nearly to the surface (discovered when a drill rig wheel broke through a surface soil bridge).

* The Bouguer gravity anomaly represents gravity survey data which have been corrected for instrument drift, tidal variation, latitude differences between survey stations, and elevation differences between stations (includes the free-air and Bouguer corrections) and between each station and surrounding terrain features (terrain correction).

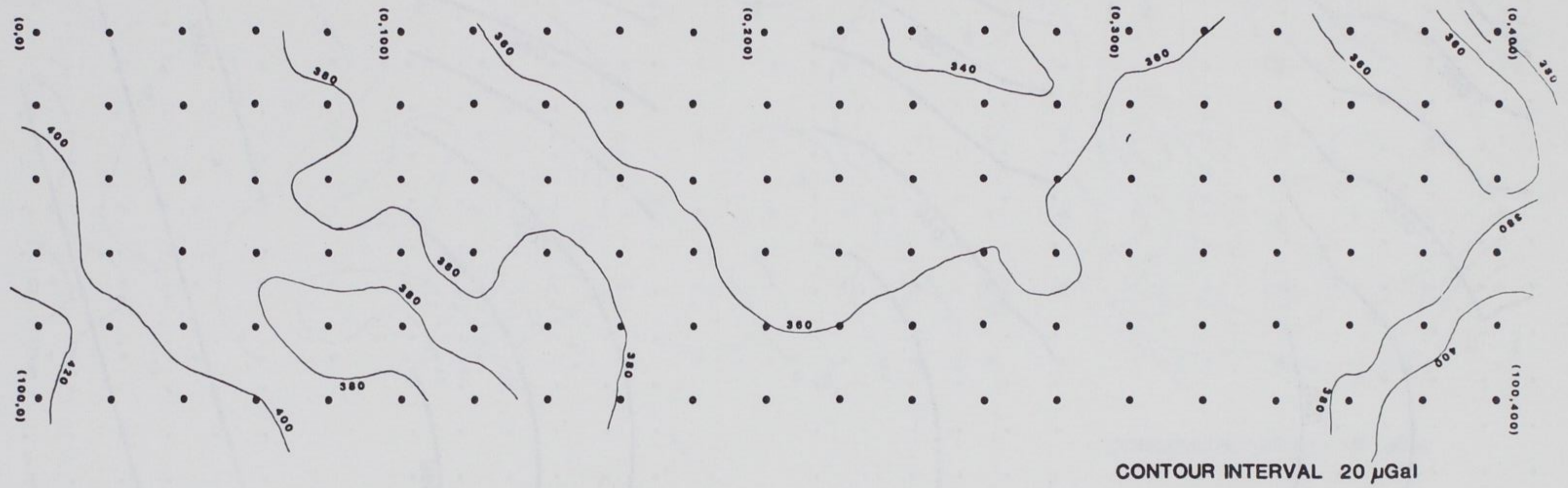


Figure 22. Bouguer gravity anomaly map, Manatee Springs site

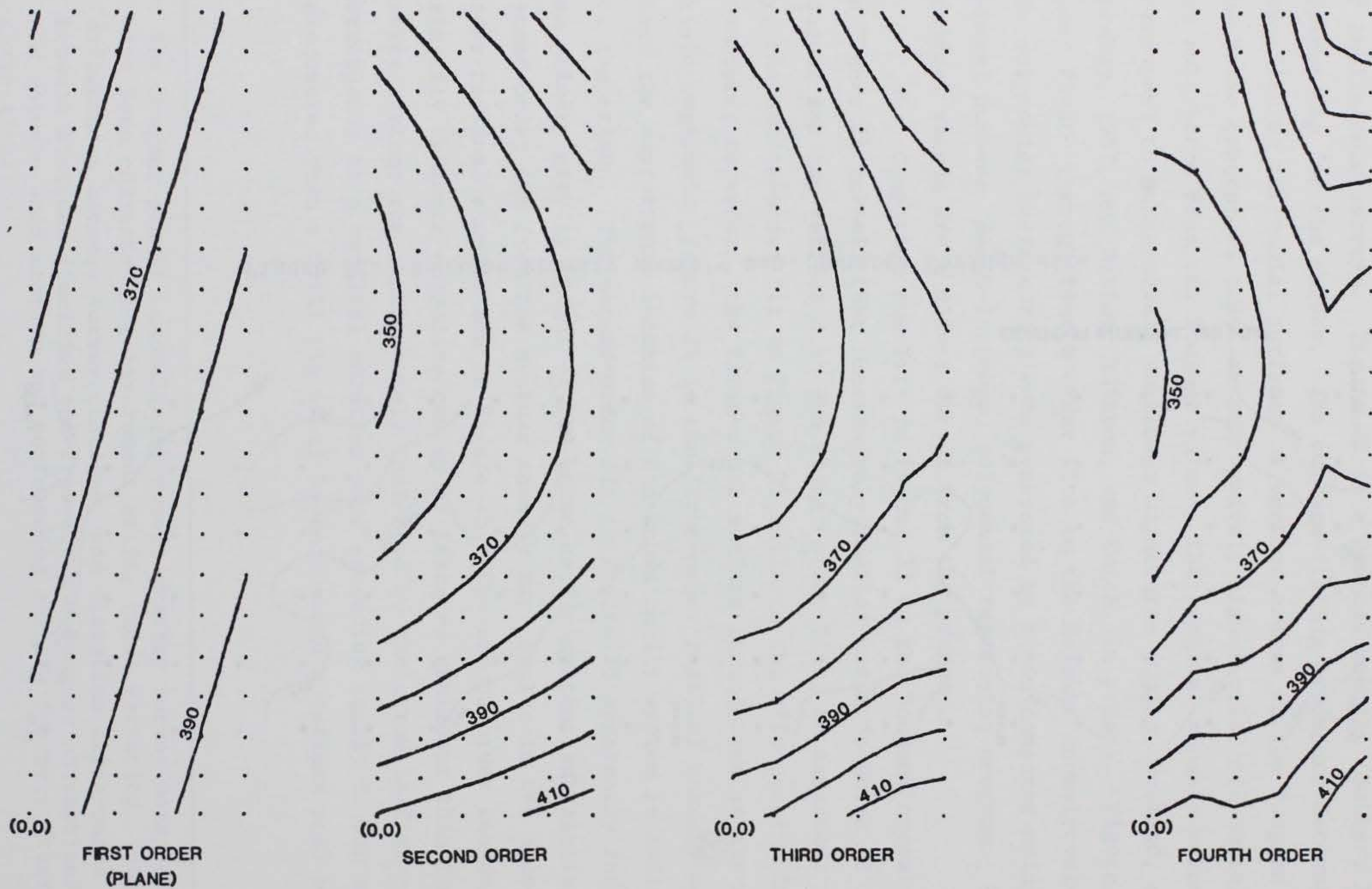


Figure 23. First- through fourth-order polynomial surface fits to the Bouguer gravity data (see Figure 13), contour interval = 10 μ Gal

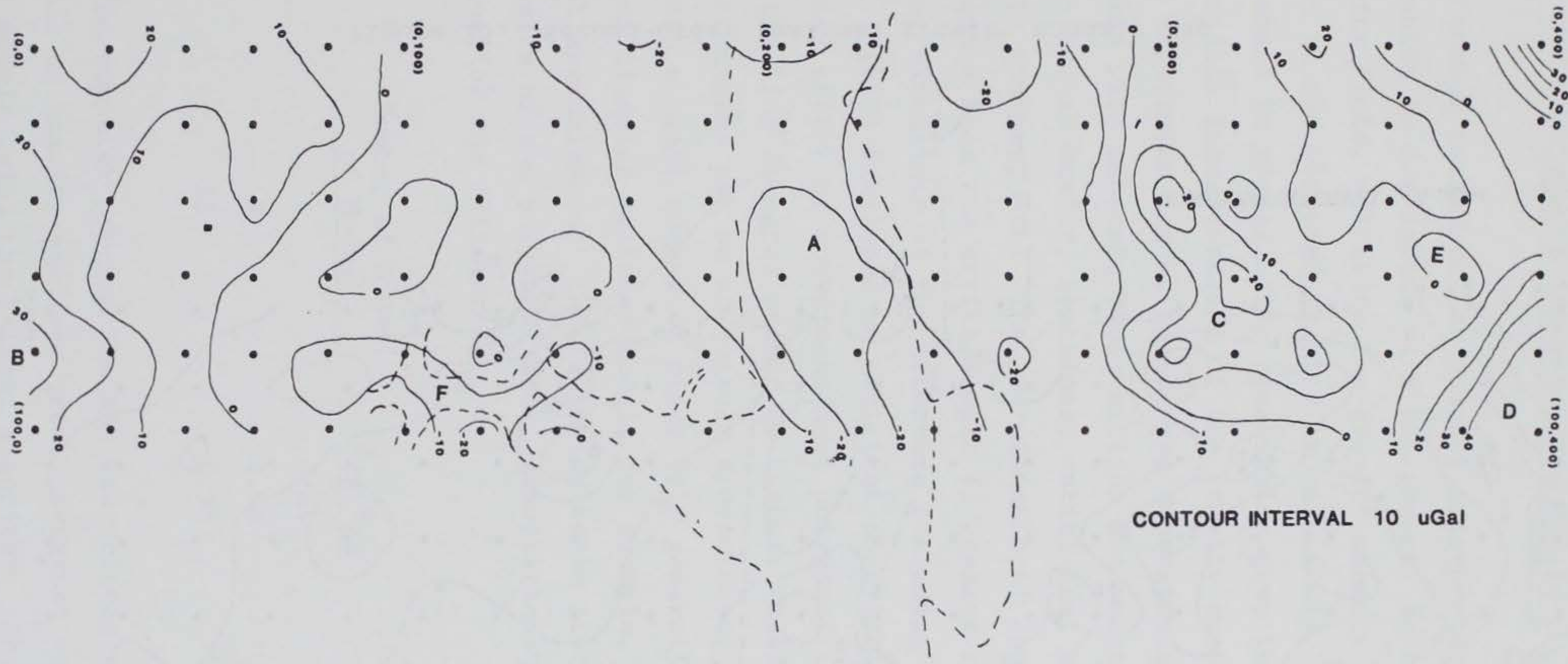


Figure 24. First-order residual gravity anomaly map

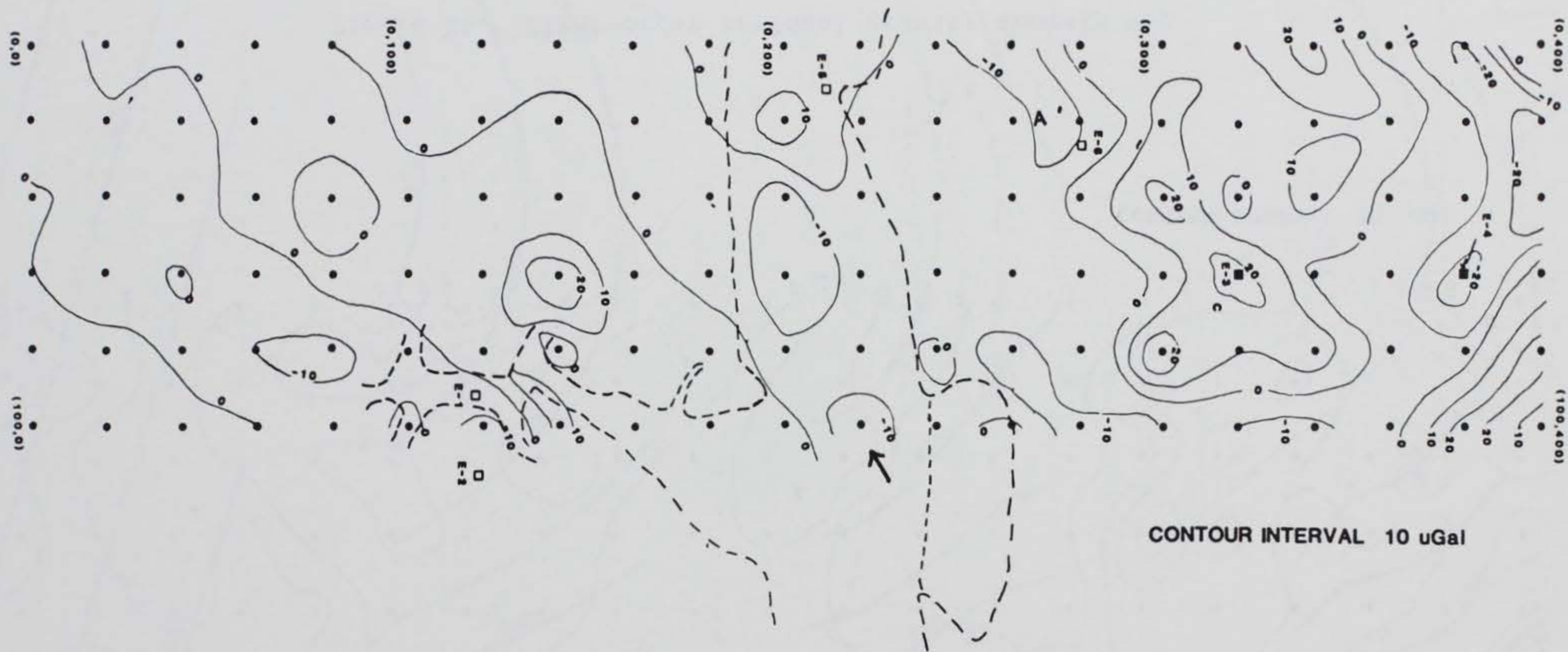


Figure 25. Second-order residual gravity anomaly map

Gravity Interpretation by Two-Dimensional
Polygonal Cross-Section Models

55. A common procedure for gravity interpretation is to postulate a model which is consistent with the general features of the observed gravity field, calculate the gravity anomaly for that model, and compare it to the observed gravity anomaly field. If the gravity field of the model is geologically reasonable, then the model can be taken as a possible interpretation of the gravity anomaly (Butler, 1980a). Many geologic structures can be considered approximately two-dimensional, i.e., horizontal with constant cross section and constant strike, e.g., faults, block-faulted basins, synclines, anticlines, buried river valleys, cavity systems, etc. The two-dimensional approximation is generally adequate when the strike length is greater than four to six times all other dimensions of the structure including the depth. Talwani et al. (1959) developed an efficient algorithm for computing the gravitational effect of two-dimensional polygonal cross section models using the line integral method of Hubbert (1948). Most two-dimensional structures can be adequately approximated in cross section by polygons with a small number of sides (<10 generally). In the case of a horizontal circular cylinder model, for example, which is inscribed by a polygonal approximation, the following table lists the ratio of the maximum value of the polygonal model gravitational effect (g_{zM}) to the exact value for the cylinder g_{zE} :

<u>Number of Sides of Model</u>	<u>g_{zM}/g_{zE}</u>
4	0.64
8	0.90
16	0.98

56. The computer program TALGRAD was written to compute gravity as well as gravity-gradient profiles across arbitrary, polygonal cross-section models using the Talwani algorithm. This program has

proven extremely useful for predicting the gravity anomalies to be expected from various known or postulated structures as well as for interpreting gravity data in an iterative fashion. Figure 25 is an example of the use of TALGRAD to compute the gravity anomaly to be expected from the main cavity at the Manatee Springs site (using approximate depths and cross-section dimensions from cave diver reports). TALGRAD as well as further examples of its use will be discussed later in this Part.

TALGRAD: A Computer Program for Computing Gravity and Gravity-Gradient Profiles Over Two-Dimensional Models

57. TALGRAD uses the procedure developed by Hubbert (1948) and Talwani et al. (1959) to compute gravity and gravity-gradient profiles over two-dimensional models. Actually, gravity profiles are computed on the surface ($z = 0$) and at selected elevations above the surface ($z = -\text{DELZ}, -2 \text{ DELZ}, \dots, -\text{SMAX}$) at discrete profile points (separated by DELX). The vertical and horizontal gradients are then calculated as finite differences or interval gradients. A listing of TALGRAD is given in Appendix F.

Input data

58. All input is in free-field format and the program will call for the input variables by name. All length dimensions must be consistent; either kft (1000's of ft) or m are acceptable. The density contrast must be in g/cm^3 . Input data are explained as follows:

Input No. 1: K, DELX, DELZ, ZMAX

K--number of profile stations

DELX--distance between stations

DELZ--vertical distance between elevations at which gravity is computed at each profile station

ZMAX--maximum elevation at which gravity is computed (ZMAX is an integral multiple of DELZ)

Input No. 2: NPOLY

NPOLY--number of closed polygons comprising the model

Input No. 3:

Dimensions in kft (enter 1) or metres (enter 2)

Input No. 4: DELRO, N

DELRO--density contrast for a polygon
N--number of corners in a polygon

Input No. 5: X1, Z1, X2, Z2, ..., XN, ZN

X,Z--coordinate pairs for polygon corners, N-pairs to
be input in clockwise order

(The preceding two input sequences, No. 4 and 5, will be repeated once
for each polygon. Also these two input sequences are repeated for each
elevation in the calculation.)

Input No. 6:

Option to calculate gravity gradients (enter 1) or not
(enter 2) and program execution will terminate.

Input No. 7: DELXX, DELZZ

DELXX, DELZZ--intervals to be used for horizontal and
vertical gradient calculations in incre-
ments of DELX and DELZ, respectively

Input No. 8: HZ

HZ--elevation for which the horizontal gradient profile
is desired, in increments of DELZ (=0 to calculate
profile on the surface $z = 0$)

Input No. 9:

Option to recalculate gradients for different values of
DELXX and DELZZ--Yes, enter 1; No, enter 2

Program output

59. Both tabular listings and plots are produced by the program,
and many of the lists and plots are optional. The output sequence is
described below:

- a. Following Inputs 4 and 5 for each polygon, a listing
summarizes all the input data for that polygon.
- b. An optional listing of the results of the gravity pro-
file calculation is generated for elevation 0.
- c. An optional plot of the gravity profile for elevation 0
is produced.
- d. Optional listings and plots are produced for each addi-
tional elevation in the calculation.
- e. A listing of the vertical gradient profile calculations
is generated.
- f. A plot of the vertical gradient profile is produced.

- g. A listing of the horizontal gradient profile calculations is generated.
- h. A plot of the horizontal gradient profile is produced, where the value is plotted at the midpoint of the horizontal interval DELXX.
- i. An optional gradient space plot is produced (i.e., $g_{z,x}$ versus $g_{z,z}$).
- j. An optional plot of the square of the modulus ($a^2(x)$) of the analytic signal is produced, where $a^2(x) = g_{z,z}^2(x) + g_{z,x}^2(x)$.
- k. The entire sequence of output from item e to j can be repeated with different values of DELXX and DELZZ, if desired.

Examples

60. Example 1. Figure 26 is an example of the use of TALGRAD to compute the gravity profile over a model of the Manatee Springs main

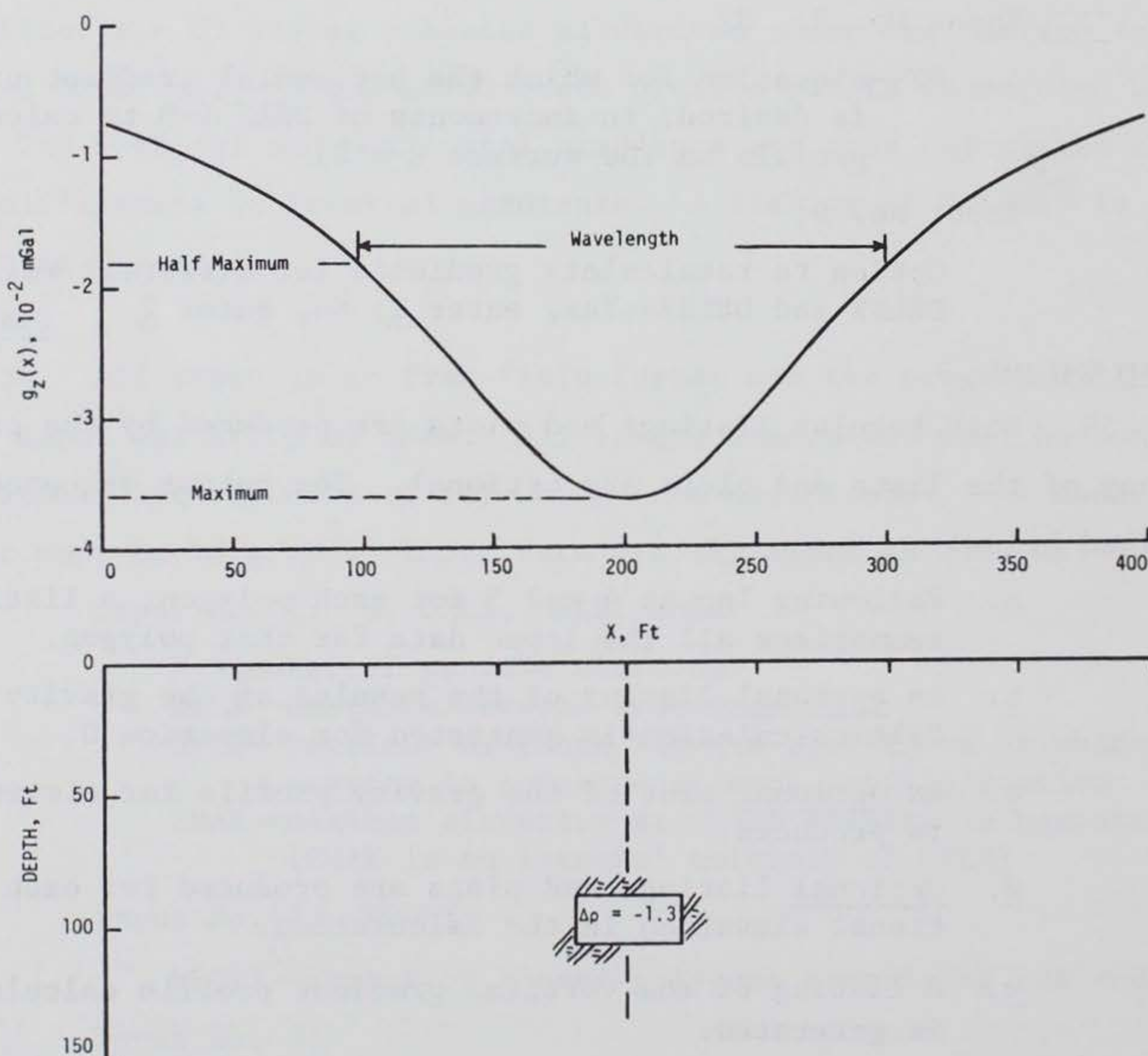


Figure 26. Two-dimensional model of the main cavity at the Manatee Springs site and a gravity profile computed by TALGRAD

cavity; a complete listing of the input data and output listings for this example is given in Figure 27.

61. Example 2. Fugro National, Inc. (1980) and McLamore and Walen (1979) report the results of an extensive gravity survey in and around Dry Lake Valley, Nev., in the Basin and Range Province. Using the three-dimensional gravity inversion computer program of Cordell (1970), the gravity data were inverted to yield a three-dimensional model of the subsurface. For the inversion, a constant density contrast (of -0.45 g/cm^3) was used. Figure 28 shows the residual gravity anomaly map, and Figure 29 shows depth to basement rock contours from the three-dimensional inversion. A section view model along profile AA' is given in Figure 30. Since block faulting is the predominant structural style of the area, the interpretation is reasonable. As an example of the use of TALGRAD, gravity and gravity-gradient profiles along AA' were computed from the model in Figure 30. The gravity profile, the horizontal and vertical gravity-gradient profiles, a gradient space plot, and a plot of the square of the modulus of the analytic signal are shown in Figures 31-34, respectively. Selected data from the three-dimensional inversion results are shown in Figure 31 for comparison. This example will be considered in greater detail later in this Part.

Determination of Vertical Gravity-Gradient Profiles
by a Hilbert Transform Procedure

62. Butler (1980a, b) suggests a procedure by which structural model parameters can be determined by a simultaneous analysis of both the vertical and horizontal gravity-gradient profiles across a structure. Except for shallow structures (<10 to 15 m depth), the use of a short tripod and "microgal" gravimeter to determine interval vertical gradients does not appear practical due to high levels of "gradient noise" caused by very shallow density variations. The vertical gradient profile can, however, be calculated from the horizontal gradient profile if the source of the gravity anomaly is approximately two-dimensional. This relation is expressed

```

K, DELX, DEL Z, ZMAX
=41, .01, 0, 0
NPOLY
=1
DIMENSION IN FEET (TYPE 1) OR METERS (TYPE 2) ?
=1
POLYGON-- 1
DELRO, N
=-1, 3, 4
X1, Z1, . . . . . XN, ZN
=.18, .088, .22, .088, .22, .1056, .18, .1056

```

```

STATIONS      POLYG. SIDES      DENSITY
  41              4          -1.300000

```

```

      VERTEX      DISTANCE      DEPTH
      1           0.180000      0.088000
      2           0.220000      0.088000
      3           0.220000      0.105600
      4           0.180000      0.105600

```

```

DO YOU WANT TO PRINT GZ FOR H= 0.  --YES (1), NO (2)
=1

```

```

-----ELEVATION = 0. -----

```

STATION	X	GZ(X)
1	0.	-0.007334
2	0.010000	-0.007965
3	0.020000	-0.008673
4	0.030000	-0.009448
5	0.040000	-0.010284
6	0.050000	-0.011175
7	0.060000	-0.012116
8	0.070000	-0.013103
9	0.080000	-0.014135
10	0.090000	-0.015217
11	0.100000	-0.016347
12	0.110000	-0.017523
13	0.120000	-0.018743
14	0.130000	-0.020006
15	0.140000	-0.021310
16	0.150000	-0.022654
17	0.160000	-0.024036
18	0.170000	-0.025454
19	0.180000	-0.026906
20	0.190000	-0.028391

Figure 27. TALGRAD input/output for the example in Figure 25; user input indicated by an '=' sign (Continued)

21	0.200000	-0.032016
22	0.210000	-0.037537
23	0.220000	-0.034541
24	0.230000	-0.034344
25	0.240000	-0.034702
26	0.250000	-0.030308
27	0.260000	-0.027802
28	0.270000	-0.025318
29	0.280000	-0.022943
30	0.290000	-0.020731
31	0.300000	-0.018710
32	0.310000	-0.016887
33	0.320000	-0.015255
34	0.330000	-0.013803
35	0.340000	-0.012516
36	0.350000	-0.011375
37	0.360000	-0.010364
38	0.370000	-0.009468
39	0.380000	-0.008673
40	0.390000	-0.007985
41	0.400000	-0.007394

DO YOU WANT PLOTS OF GRAVITY PROFILES?--YES(1), NO(2)

=1

PLOT GRAVITY PROFILE FOR H= 0.

READ X0,Y0,SPX,SPY,IA, IDASH, THETA

=1.5,50.,.001391,0.0,0

READ HTX,XL,XS,NDX,NPX,SPX,ITX

=.1,8,0.0,0,0,0

READ HTY,YL,YS,NDY,NPY,SPY,ITY

=.1,4,-4.0,-2,0,0

READ X-LABEL

=X, FT

READ Y-LABEL

=GZ(X), MGAL

A

DO YOU WANT TO CALCULATE GRAVITY GRADIENTS? TYPE 1 FOR YES, 2 FOR NO

=2

Input specifications for
producing the gravity
profile plot in Figure 25.

Figure 27. (Concluded)

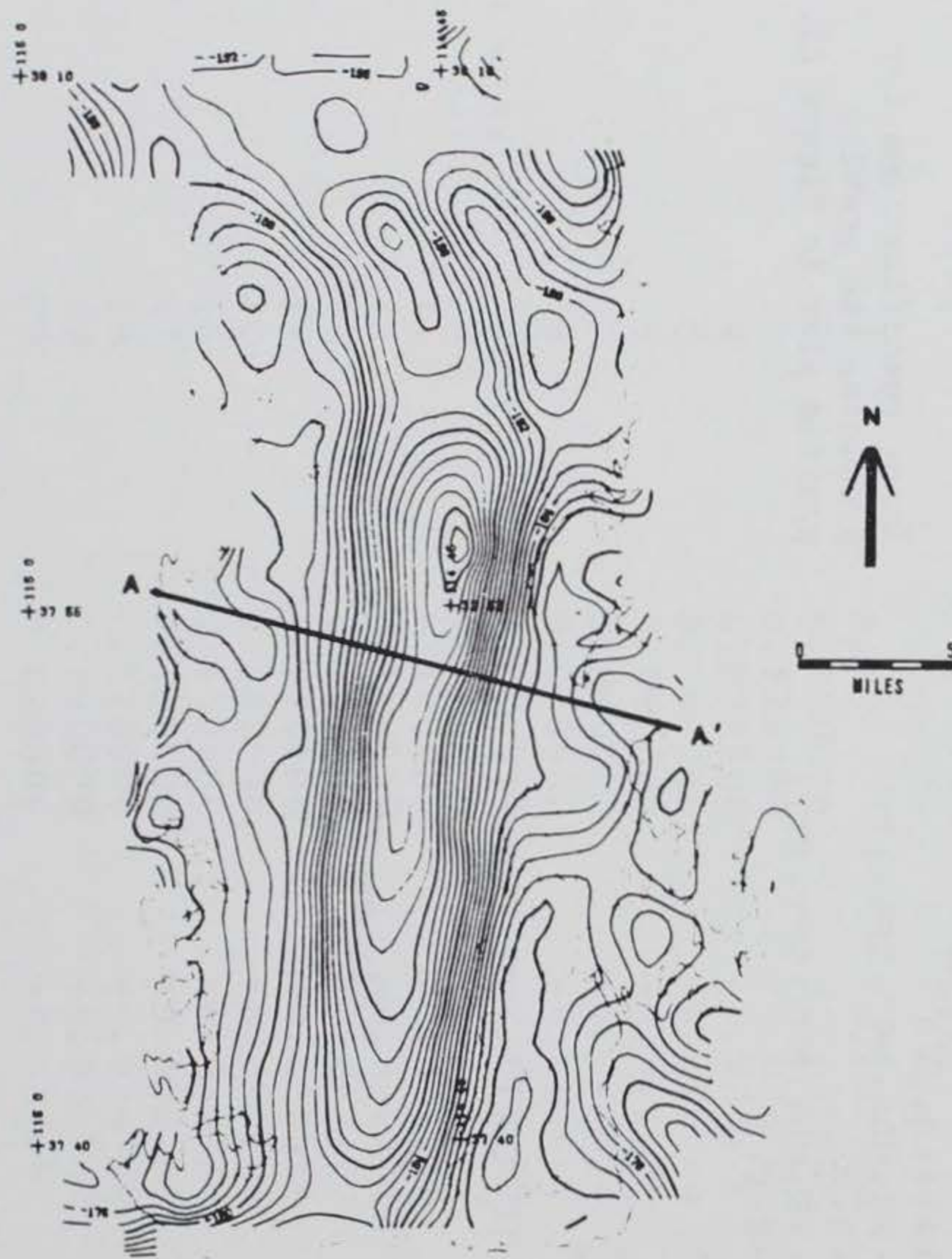


Figure 28. Dry lake valley residual anomaly contours

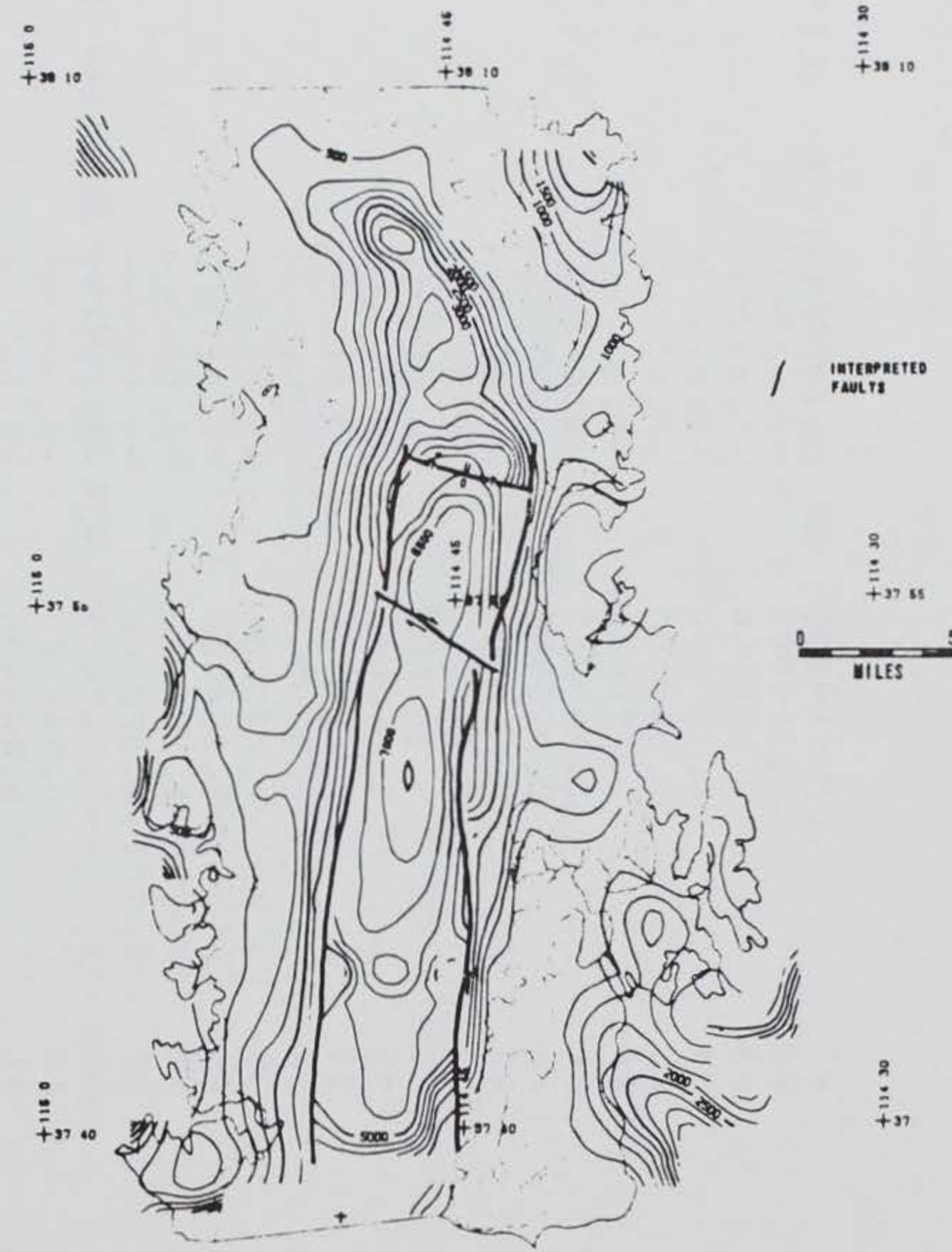


Figure 29. Dry lake valley bedrock depth contours

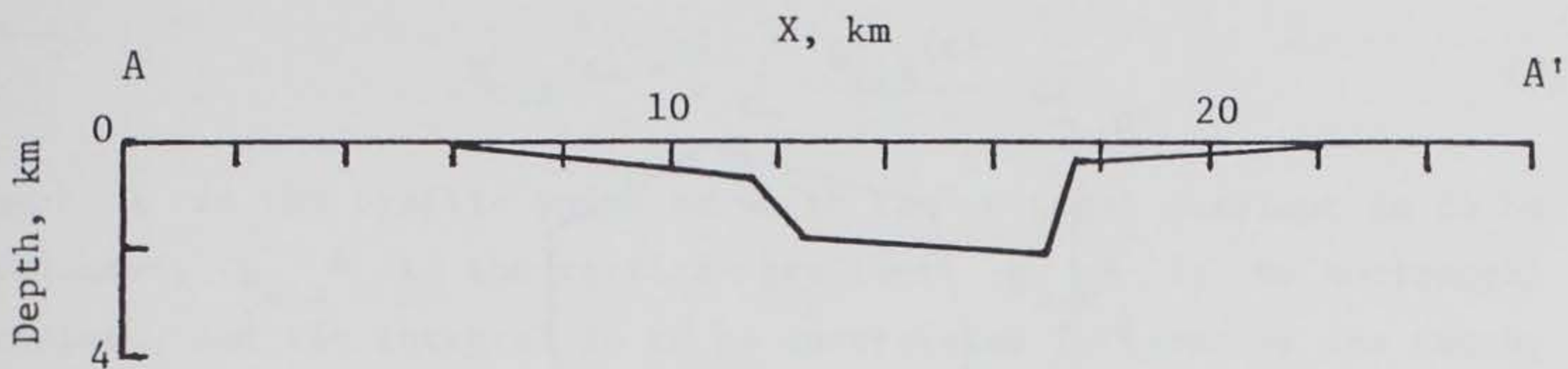


Figure 30. Structure model from 3D gravity inversion

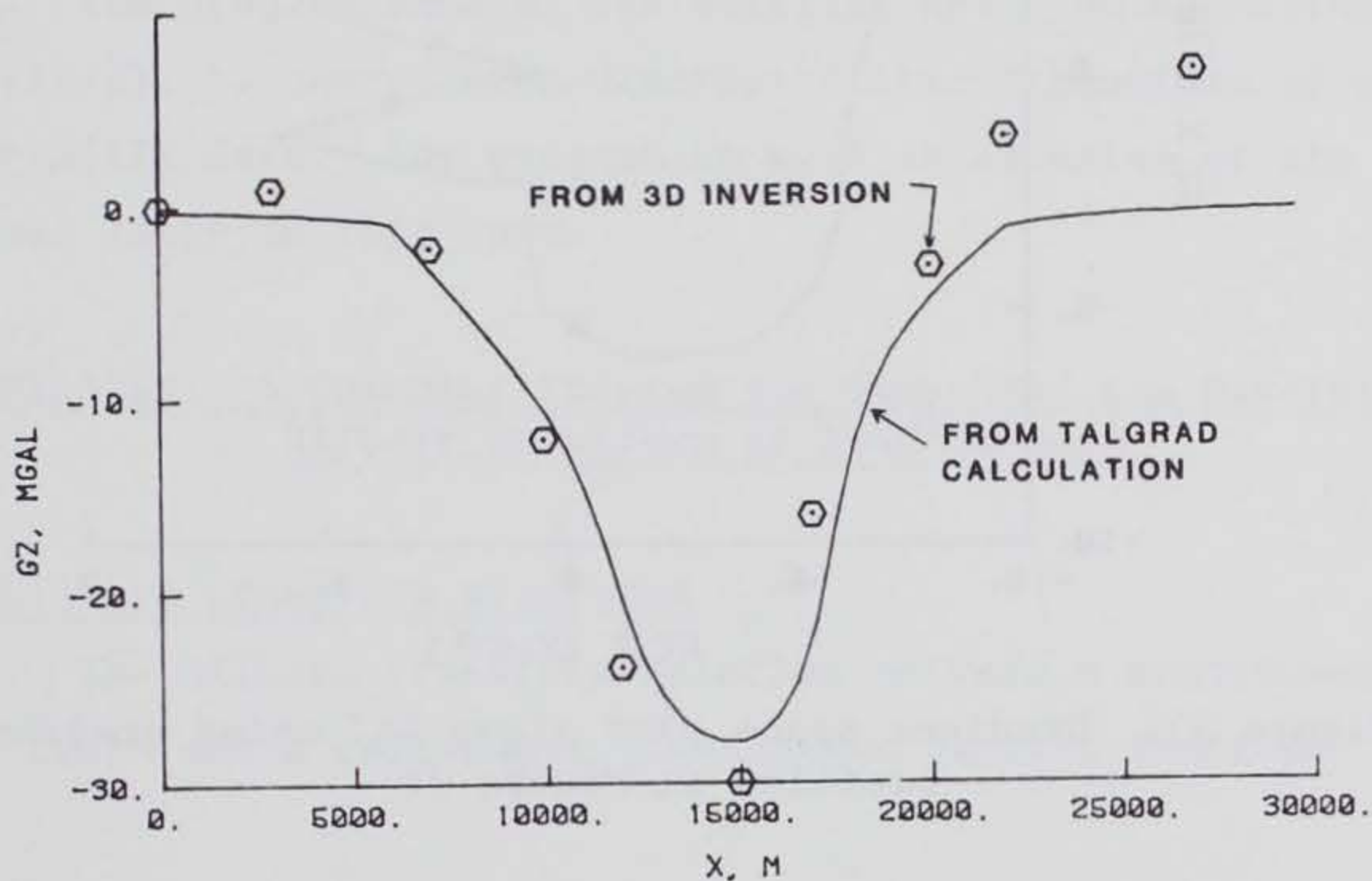


Figure 31. Comparison of gravity profile along AA' from TALGRAD calculation using the model in Figure 30 with the results of a 3D gravity inversion

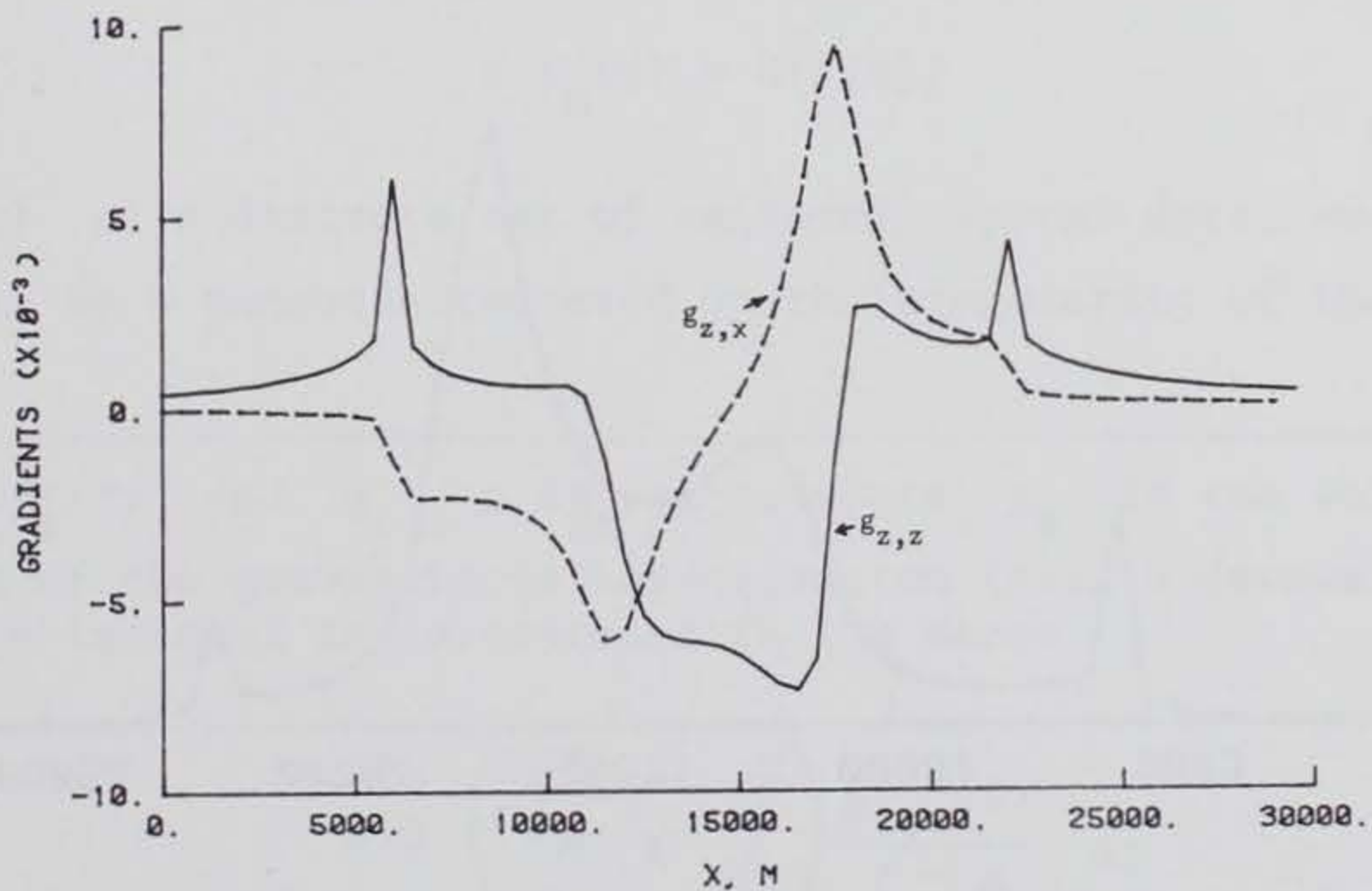


Figure 32. Gravity-gradient profiles along AA' calculated by TALGRAD using model in Figure 30

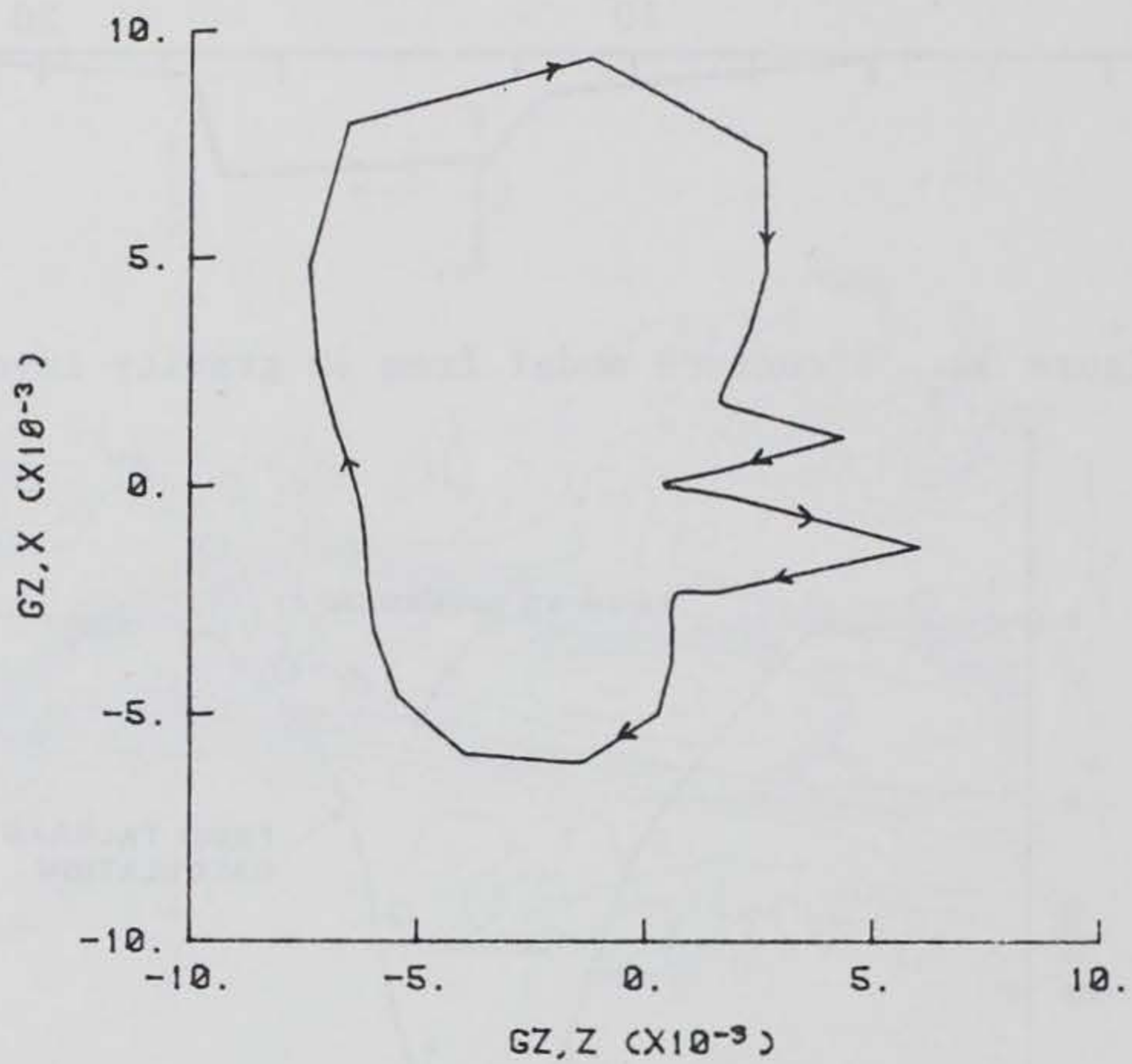


Figure 33. Gradient space plot along AA' using gradient profiles in Figure 32

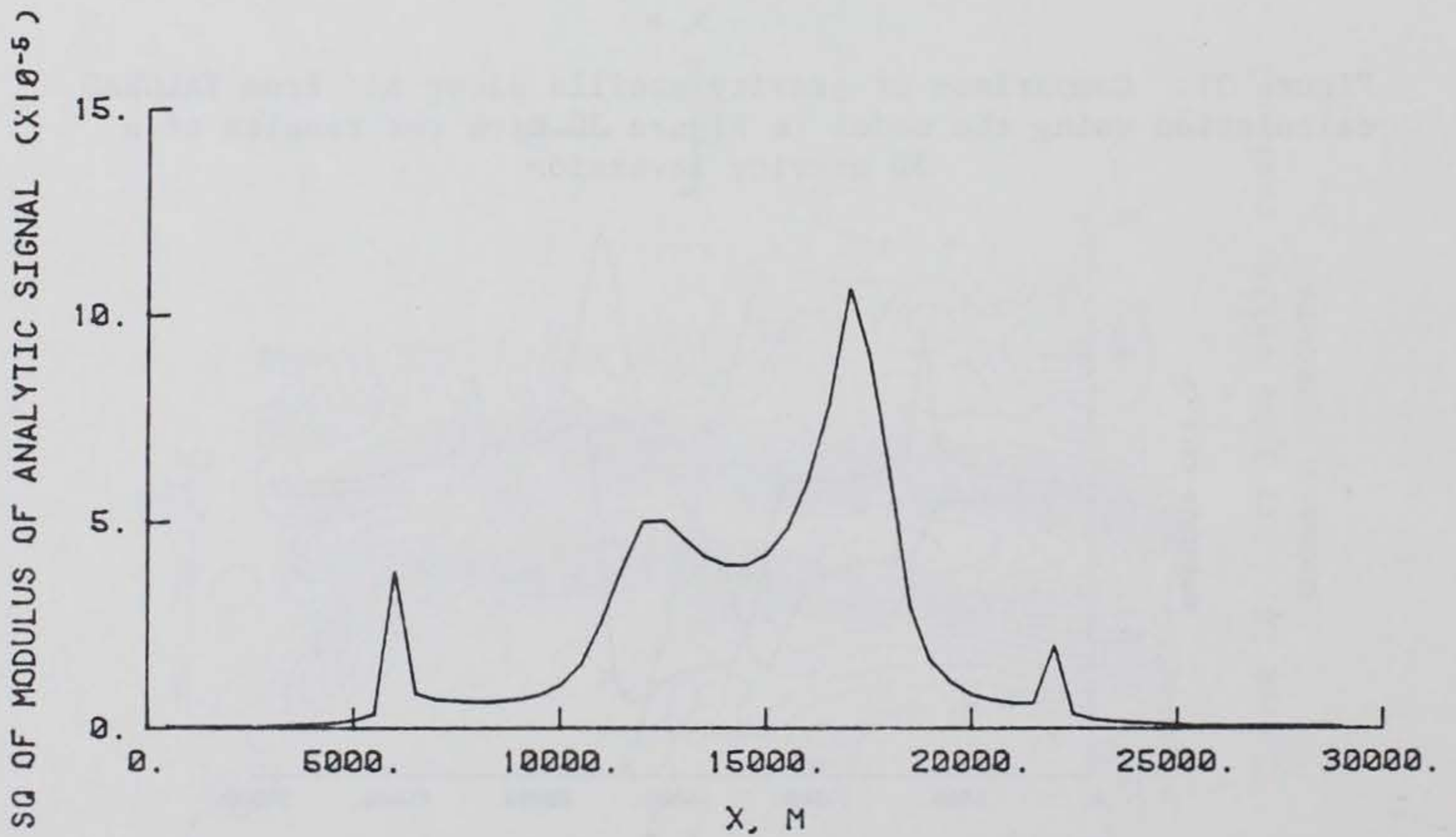


Figure 34. Square of modulus of analytic signal plot along AA'

$$g_{z,z}(x) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g_{z,x}(\zeta)}{\zeta - x} d\zeta \quad (2)$$

where x is the profile point at which the vertical gradient is to be evaluated, $g_{z,z}^*$ is the vertical gradient, $g_{z,x}^*$ is the horizontal gradient, and the integral is to be interpreted in terms of its Cauchy principal value.**

63. The program HILBERT was written, using an algorithm suggested by Shuey (1972), to compute the discrete Hilbert transform of a set of discrete profile data. The program as well as examples of its use will be discussed later in this Part.

HILBERT: A Computer Program for Computing the Discrete
Hilbert Transform of Profile Data

Discrete Hilbert transform algorithm

64. The Hilbert transform relation between a continuous profile function $f(x)$ and a continuous transformed profile function $q(x)$ is

$$q(x) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{f(\beta)}{\beta - x} d\beta$$

$$\equiv f_h(x) = H(f(x)) \quad (3)$$

Now let $f(x)$ be a discrete set of uniformly spaced data, and approximate the data by a parabola centered on the singularity of the integrand

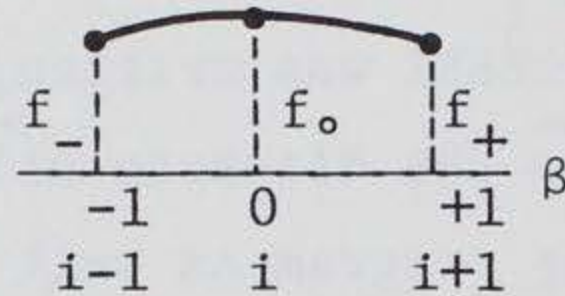
* $g_{z,z} \equiv \partial g_z / \partial z$ and $g_{z,x} \equiv \partial g_z / \partial x$, where g_z is the vertical component of the gravitational acceleration (z-axis downward)

** I.e., the integral is interpreted in the sense

$$\lim_{a \rightarrow 0} \left(\int_{-\infty}^{x-a} + \int_{x+a}^{\infty} \right) \frac{g_{z,x}(\zeta)}{\zeta - x} d\zeta$$

$\beta=x$ (passing through β and the two adjacent points) and with a linear fit to all other pairs of points in the profile data. Using this approximation to the discrete set of profile data, Equation 3 can be numerically integrated in a straightforward manner.

65. The diagram below defines the terminology for considering the parabolic fit centered on the singularity.



66. For simplicity in the derivation, a unit digitizing interval is used and the singularity is taken to be at $\beta=0$ at the i^{th} data point. The parabolic fit to $f(\beta)$ is defined as follows:

$$f(\beta) = a + b\beta + c\beta^2 \quad (4)$$

$$\left. \begin{aligned} f(0) &= f_0 = a \\ f(+1) &= f_1 = a + b + c \\ f(-1) &= f_{-1} = a - b + c \end{aligned} \right\} \quad (5)$$

Equation 5 can be solved for the empirical constants in Equation 4 as follows

$$\begin{aligned} a &= f_0 \\ b &= \frac{f_1 - f_{-1}}{2} \\ c &= \frac{f_1 + f_{-1}}{2} - f_0 \end{aligned}$$

and Equation 2 can be written

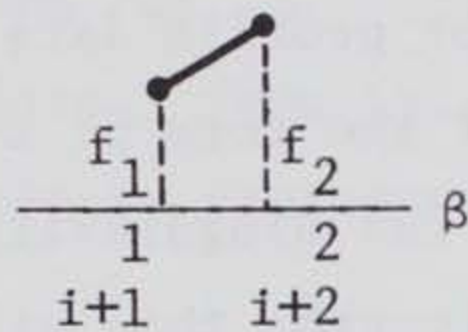
$$f(\beta) = f_0 + \left(\frac{f_1 - f_{-1}}{2} \right) \beta + \left(\frac{f_1 + f_{-1}}{2} - f_0 \right) \beta^2 \quad (6)$$

Equation 6 can now be substituted into Equation 3 to find the contribution to the integral from the parabolic fit centered on the singularity

$$\frac{1}{\pi} \int_{-1}^1 \frac{f(\beta)}{\beta} d\beta = \frac{1}{\pi} \left[f_0 \ln|\beta| + \left(\frac{f_1 - f_{-1}}{2} \right) \beta + \frac{1}{2} \left(\frac{f_1 + f_{-1}}{2} - f_0 \right) \beta^2 \right]_{-1}^{+1}$$

$$= \frac{1}{\pi} (f_1 - f_{-1}) \quad (7)$$

67. Examining the linear fit to the first two data points to the right of the singularity, as an example, yields



$$f(x) = a + bx$$

$$f_1 = a + b\beta_1$$

$$f_2 = a + b\beta_2$$

$$a = f_1 - b\beta_1$$

$$b = (f_2 - f_1) / (\beta_2 - \beta_1)$$

$$f(\beta) = f_1 + \left(\frac{f_2 - f_1}{\beta_2 - \beta_1} \right) (\beta - \beta_1)$$

$$= \frac{f_1\beta_2 - f_2\beta_1}{\beta_2 - \beta_1} + \frac{(f_2 - f_1)\beta}{\beta_2 - \beta_1}$$

$$= \frac{f_1(\beta - \beta_1) - f_2(\beta_1 - \beta_1) + (f_2 - f_1)(\beta - \beta_1)}{\beta_2 - \beta_1} \quad (8)$$

Equation 8 can be substituted into Equation 2 to evaluate the form of one of the terms resulting from the successive linear fits to pairs of data points:

$$\frac{1}{\pi} \int_{\beta_1}^{\beta_2} \frac{f(\beta)}{\beta - x} d\beta = \frac{1}{\pi} \left[\frac{f_1(\beta_2 - x) - f_2(\beta_1 - x)}{\beta_2 - \beta_1} \ln \left(\frac{\beta_2 - x}{\beta_1 - x} \right) + (f_2 - f_1) \right] \quad (9)$$

If a unit digitizing interval is again assumed, $\beta_2 - \beta_1 = 1$.

68. The complete expression for the numerical evaluation of Equation 3 for a discrete set of profile data will be the sum of Equation 7 and a series of terms of the form of Equation 9 for all data pairs to the right and left of the singularity. Necessarily, in practice, the profile will be finite in length; this will cause no problem in regard to the limits of integration of Equation 3 if all values of $f(\beta)$ are zero beyond the ends of the profile, which can be simulated by adding a zero to each end of the discrete data set. If the profile is a "residual" profile which approaches zero at the ends of the data set, then the simple procedure of dropping the profile to zero outside the data will present no problems. Otherwise, a more elaborate extrapolation to zero beyond the data may be needed. If there are N data values in the set, shift the data one position to the right and add a zero at $n = 1$ and $n = N + 2$. Considering this revised data set, the result of summation of Equation 7 with all the terms of the form of the second term of Equation 9 is the value of $\frac{1}{\pi} (f_{N+2} - f_1)$ which is identically zero. Thus, remaining is a summation of terms of the form of the first term of Equation 9 involving data pairs to the right and left of the singularity (but not including the singularity itself). The result will be called the discrete Hilbert transform $H^D(f(x))$ or $f_H^D(x)$. The above procedure is repeated for all profile positions x .

Program input and output

69. The computer code HILBERT, listed in Appendix G, evaluates the discrete Hilbert transform using the algorithm discussed above.

Input to HILBERT consists of the number of data values N , the actual profile spacing between points $DELX$, and the profile values T . Output consists of a tabular listing of profile position X , profile data value T , discrete Hilbert transform H , the value $A(=T^2 + H^2)$, and plots of T versus X , H versus X , H versus T , and A versus X . In practice, T will generally be the horizontal gravity gradient (tabular column labeled GX,X) and H will be the computed vertical gravity gradient (tabular column labeled GZ,Z).

Example: a test of the discrete Hilbert transform algorithm

70. A procedure for testing the proposed algorithm for evaluating the discrete Hilbert transform can be formulated by examining the properties of the Hilbert transform. From the definition of convolution (denoted by $*$), Equation 2 can be expressed as:

$$f_H(x) = \left(-\frac{1}{\pi x}\right) * f(x) \quad (2)$$

Applying the convolution theorem gives:

$$F(f_H(x)) = i \operatorname{sgn}(s) F(f(x))$$

where F denotes the Fourier transform and s is the transform variable. Inverting this equation gives

$$F(f(x)) = -i \operatorname{sgn}(s) F(f_H(x))$$

$$\begin{aligned} f(x) &= \left(\frac{1}{\pi x}\right) * f_H(x) \\ &= -\left(-\frac{1}{\pi x}\right) * f_H(x) \\ &= -\left(\frac{1}{\pi}\right) \int_{-\infty}^{\infty} \frac{f_H(\beta)}{\beta - x} d\beta \end{aligned}$$

$$f(x) = -H(f_H(\beta)) \quad (10)$$

Equation 10 suggests the following test for the discrete Hilbert transform algorithm:

$$\begin{aligned} \text{if } f_H^D(x) &\approx f_H(x) , \\ \text{then } H^D(f_H^D(x)) &\approx -f^D(x) \end{aligned} \quad (11)$$

where $f^D(s)$ denotes the discrete profile data set. That is, two successive applications of the discrete Hilbert transform to the profile data set should yield the negative of the original profile data set.

71. Consider the simple functional relation:

$$f(x) = \frac{1}{1+x^2} \quad (12)$$

which has the analytic Hilbert transform (Erdelyi, 1954)

$$f_H(x) = \frac{-x}{1+x^2} \quad (13)$$

Equation 12 is a symmetric function with half-width at half-maximum equal to 1.0, maximum value equal to 1.0 at $x = 0$, and asymptotes which approach 0 in both directions. As a first test, the function $f(x)$ is sampled or discretized at increments $\Delta x = 1$ over the range $-10 \leq x \leq 10$ and set equal to zero outside this range. Figure 35a contains the tabular output resulting from inputting $f^D(x)$, with $f_H^D(x)$ being the computed discrete Hilbert transform. In Figure 35b, $f_H^D(x)$ is the input data and $H^D(f_H^D(x))$ is the output (i.e., the output represents two successive Hilbert transform operations applied to $f^D(x)$). Plots of $f^D(x)$, $f_H^D(x)$, and $H^D(f_H^D(x))$ are shown in Figure 36. Qualitatively, $H^D(f_H^D(x))$ can be recognized as the negative of $f^D(x)$; however, the maximum absolute value is 0.71 compared to 1.0 for $f^D(x)$, the half-width at half-maximum is 1.5 compared to 1.0 for $f^D(x)$, and the two ends of the calculated profile cross the x-axis while the $f^D(x)$ profile does not.

x	$f^D(x)$	$f_H^D(x)$	x	$f_H^D(x)$	$H^D(f_H^D(x))$
-10.0	0.00990	0.10598	-10.0	0.10598	0.11857
-9.0	0.01219	0.11373	-9.0	0.11373	0.07730
-8.0	0.01538	0.12621	-8.0	0.12621	0.06254
-7.0	0.02000	0.14276	-7.0	0.14276	0.05120
-6.0	0.02702	0.16485	-6.0	0.16485	0.03959
-5.0	0.03846	0.19527	-5.0	0.19527	0.02453
-4.0	0.05882	0.23911	-4.0	0.23911	0.00029
-3.0	0.10000	0.30589	-3.0	0.30589	-0.04874
-2.0	0.20000	0.40823	-2.0	0.40823	-0.18225
-1.0	0.50000	0.44459	-1.0	0.44459	-0.49781
0	1.00000	0.00000	0	0.00000	-0.71351
1.0	0.50000	-0.44459	1.0	-0.44459	-0.49781
2.0	0.20000	-0.40823	2.0	-0.40823	-0.18225
3.0	0.10000	-0.30589	3.0	-0.30589	-0.04874
4.0	0.05882	-0.23911	4.0	-0.23911	0.00029
5.0	0.03846	-0.19527	5.0	-0.19527	0.02453
6.0	0.02702	-0.16485	6.0	-0.16485	0.03959
7.0	0.02000	-0.14276	7.0	-0.14276	0.05120
8.0	0.01538	-0.12621	8.0	-0.12621	0.06254
9.0	0.01219	-0.11373	9.0	-0.11373	0.07730
10.0	0.00990	-0.10598	10.0	-0.10598	0.11857

Figure 35a. Discrete Hilbert transform
 f_H^D of f^D

Figure 35b. Discrete Hilbert transform
 H^D of f_H^D

Figure 35. Tabular output from HILBERT for test case with
 $\Delta x = 1$ and $-10 \leq x \leq 10$

72. To illustrate the effects of data spacing Δx and profile length, several additional tests were conducted using the same function $f(x)$. Figure 37 shows plots of $f^D(x)$, $f_H^D(x)$, and $H^D(f_H^D(x))$ for $\Delta x = 0.5$ and the same profile length as in the previous test. The maximum absolute value for $H^D(f_H^D(x))$ is now 0.86 compared to 0.71 for the previous test case and to 1.0 for $f^D(x)$. Also, the half-width at half-maximum is 1.05, very close to the value for $f^D(x)$. The behavior of the ends of the $H^D(f_H^D(x))$ profile is similar in both test cases.

73. For another test case, the data spacing is the same as the first test $\Delta x = 1$, but the profile length is doubled ($-20 \leq x \leq 20$). The maximum absolute value of $H^D(f_H^D(x))$ is 0.74 and half-width at half-maximum is 1.45. The results for this case are shown in Figure 38. The primary effect of doubling the profile length compared to the first test case is to reduce the distortion near the ends of the profile line.

74. Significant features of the above three test cases as well as three additional ones are summarized in the following tabulation:

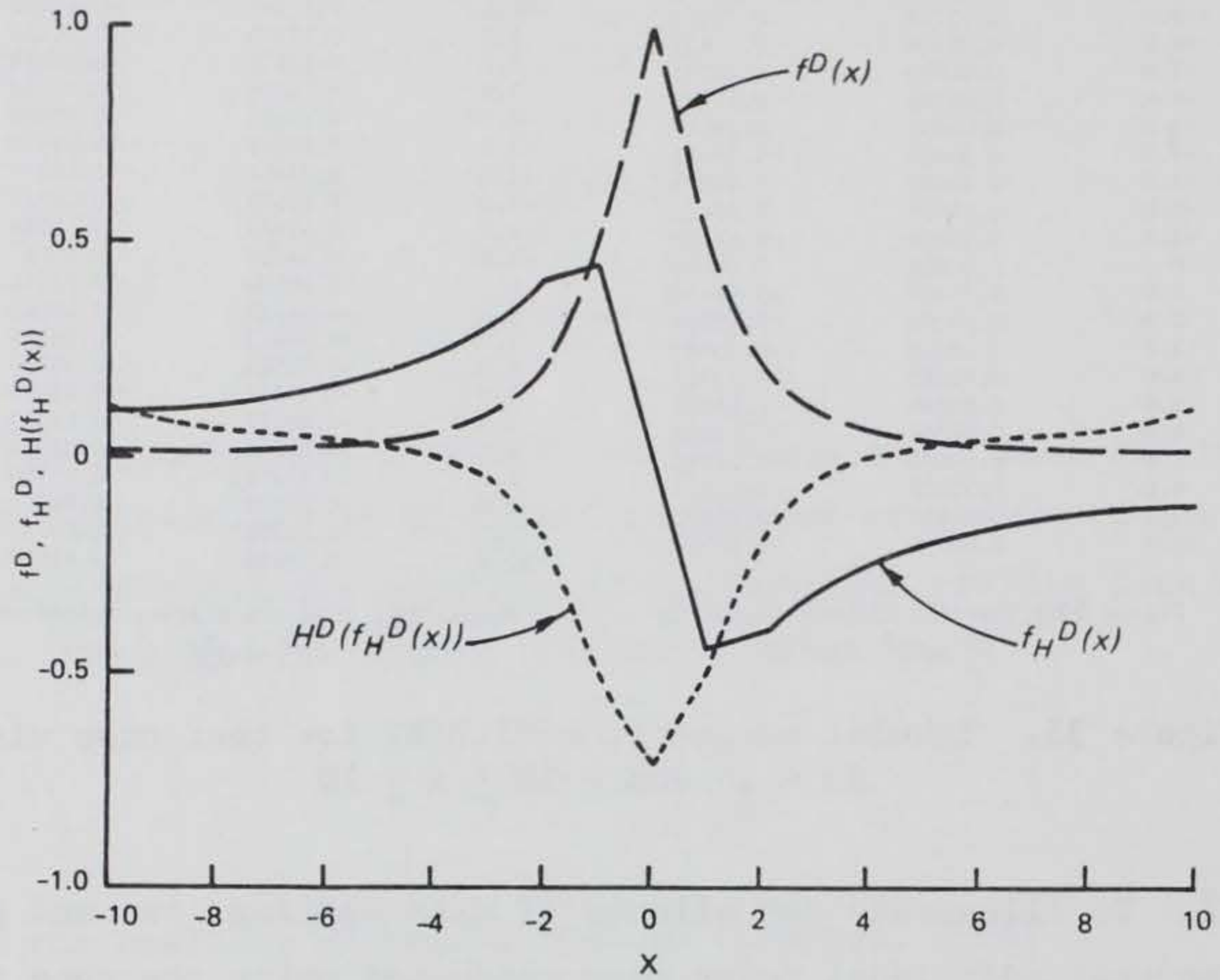


Figure 36. HILBERT test case for $\Delta x = 1$ and $-10 \leq x \leq 10$

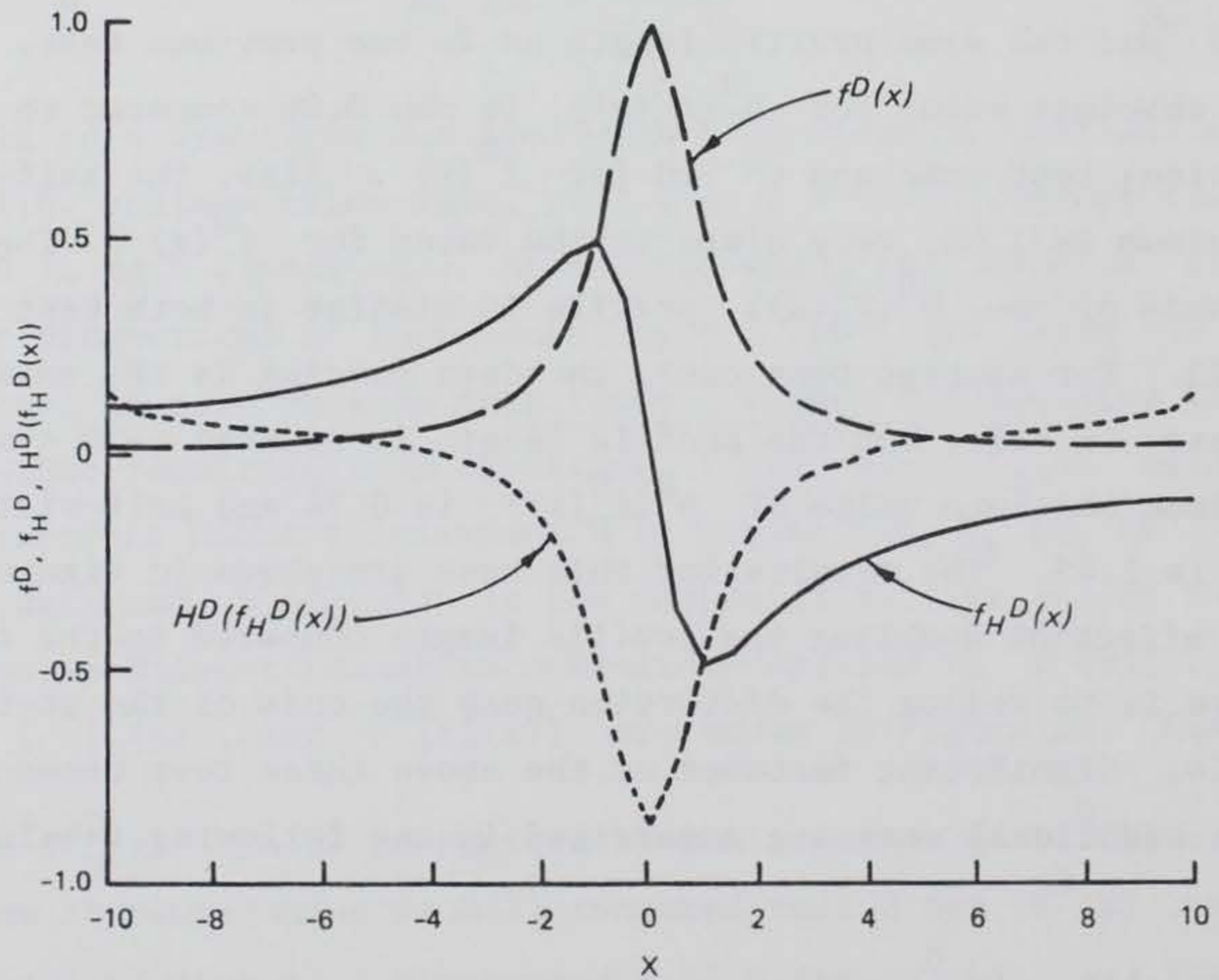


Figure 37. HILBERT test case for $\Delta x = 0.5$ and $-10 \leq x \leq 10$

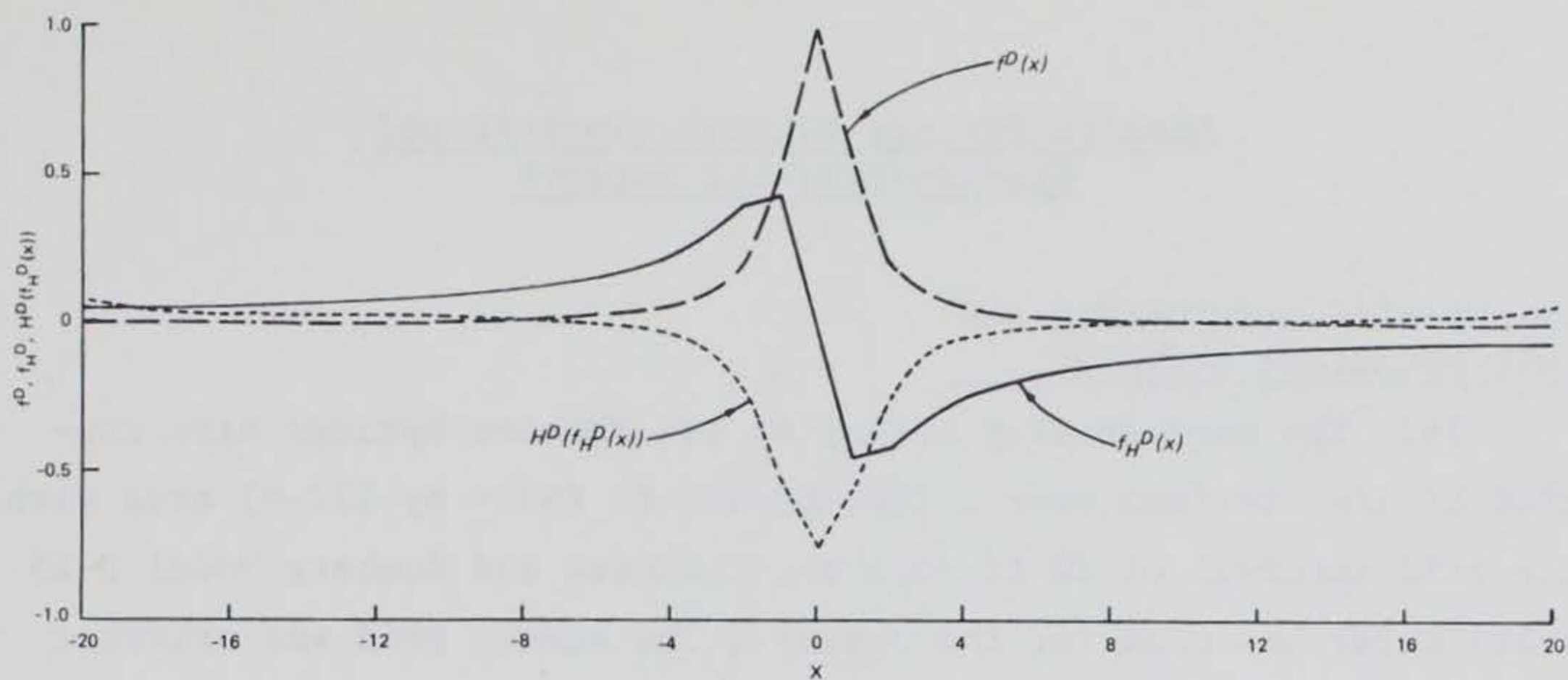


Figure 38. HILBERT test case for $\Delta x = 1$ and $20 \leq x \leq 20$

Test Case		$ H^D(f_H^D(x)) _{\max}$	Half-Width at Half-Maximum	Value at Ends of Profile
Δx	Profile Length			
1	-5, 5	0.66	2.60	0.17
0.5	-5, 5	0.80	2.00	0.22
0.25	-5, 5	0.86	1.86	0.27
1	-10, 10	0.71	1.50	0.12
0.5	-10, 10	0.86	1.05	0.14
1	-20, 20	0.74	1.45	0.07
Analytic results		1.0	1.0	$\rightarrow 0$

75. The function $f(x)$ in Equation 12 is a stringent test for the discrete Hilbert transform algorithm, since it is so sharply peaked. Sampling at $\Delta x = 1$ is rather coarse for this particular $f(x)$, yet even for this case the results of the test (two successive applications of the discrete Hilbert transform) improve significantly as the profile length is increased. Also, for a given profile length such as (-5, 5), the test results improve significantly as Δx is decreased, although the usual "law of diminishing returns" holds. Of course, simultaneously decreasing Δx and increasing the profile length is the key to improving the results. The column listing the value at the ends of the profile indicates the "errant" behavior of the ends of the doubly transformed function due to the manner in which the profile is truncated. Increasing the profile length decreases the magnitude of this "errant" behavior, while decreasing Δx increases it.

Manatee Springs Microgravimetric and Gravity-Gradient Surveys

Scope of microgravimetric and gravity-gradient surveys

76. The microgravity survey at the Manatee Springs site consisted of 186 stations over a 100- by 400-ft (~30- by 122-m) area with a basic grid interval of 20 ft (6.1 m). LaCoste and Romberg Model D-25 gravity meter was used for the survey. The survey grid was oriented approximately perpendicular to the known trend of the cavity system, as shown in Figure 3. Grid point (0,200) was used as a base station and was reoccupied on an average of once every 30 min (see Figure 19). Details of the microgravity survey procedure can be found in Butler, Whitten, and Smith (in press). In addition to the microgravity survey, a tower vertical gradient survey (Butler, 1980a) was conducted along the SW-NE line extending from (40,0) to (40,400); this survey consisted of 21 vertical gradient stations.

Residual gravity anomaly map

77. Results of the microgravity survey and the procedures used in determining the residual gravity anomaly values are discussed earlier in this Part and presented in Figures 22-25. The first-order residual anomaly map in Figure 24 is selected as the representation which reflects the gravity anomaly due to the main Manatee Springs cavity. The broad negative anomaly over the known cavity system in Figure 24 is consistent in magnitude and width with the known size and depth of the cavity system (see Figure 26). However, there are complexities or smaller anomalous features in the residual map which cannot be attributed to the main cavity; some of these smaller anomalies are due to smaller and shallower solution features or other density anomalies as discussed previously.

Vertical gradient survey results

78. The five tower measurement elevations shown in Figure 39 were utilized during the vertical gradient survey; because of difficulties in obtaining readings only five gravity values at the upper elevation h_4 were obtained along the profile line. Since the measurement sequence

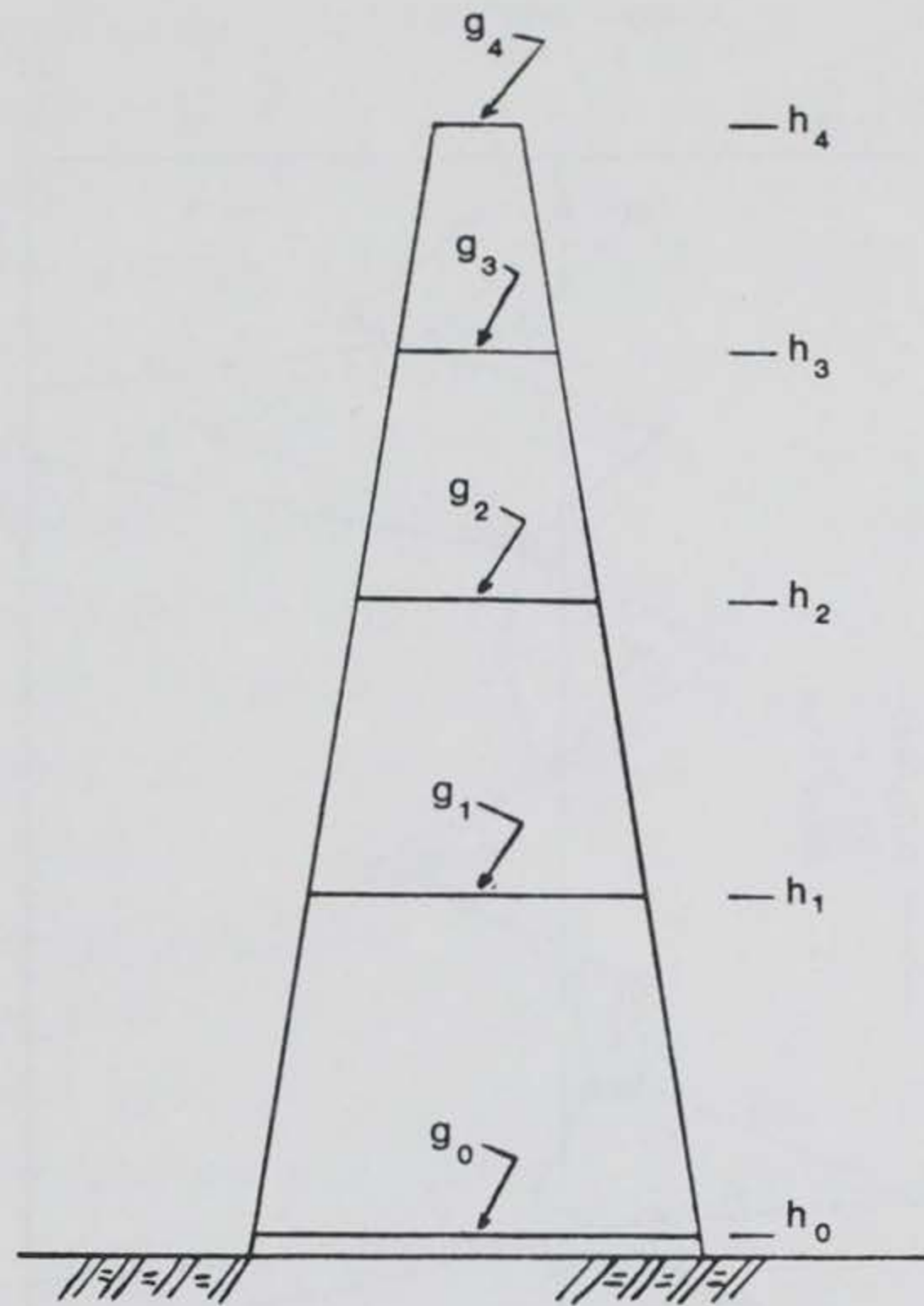


Figure 39. Illustration of the five gravity measurements and associated elevations which were utilized to determine interval vertical gradients along a selected profile line at the Manatee Springs site; nominally, $h_1 \approx 0.6$ m, $h_2 \approx 1.0$ m, $h_3 \approx 1.4$ m, $h_4 \approx 1.6$ m

at each profile location required 15 to 25 min, the ground station h_0 was reoccupied at the end of each sequence and the data were shift-corrected in the usual manner.

79. Considering elevations h_0 , h_1 , h_2 , and h_3 , six interval gradients can be determined as well as differential gradients at any point within the interval h_0 to h_3 using a parabolic fitting procedure. Results of three of the determinations of vertical gradients are shown in Figure 40: $\Delta g'_{01}/\Delta z_{01}$ and $\Delta g'_{03}/\Delta z_{03}$, where $\Delta g'_{01} = g_1 - g_0$, $\Delta z_{01} = h_1 - h_0$, and similarly for $\Delta g'_{03}$ and Δz_{03} ; $(\partial g/\partial h)_0$, which is the differential gradient at h_0 , determined from a parabolic fit to the data at h_0 , h_1 , and h_3 and evaluated at h_0 . The five values of $\Delta g'_{04}/\Delta z_{04}$ are also shown. All three profiles exhibit

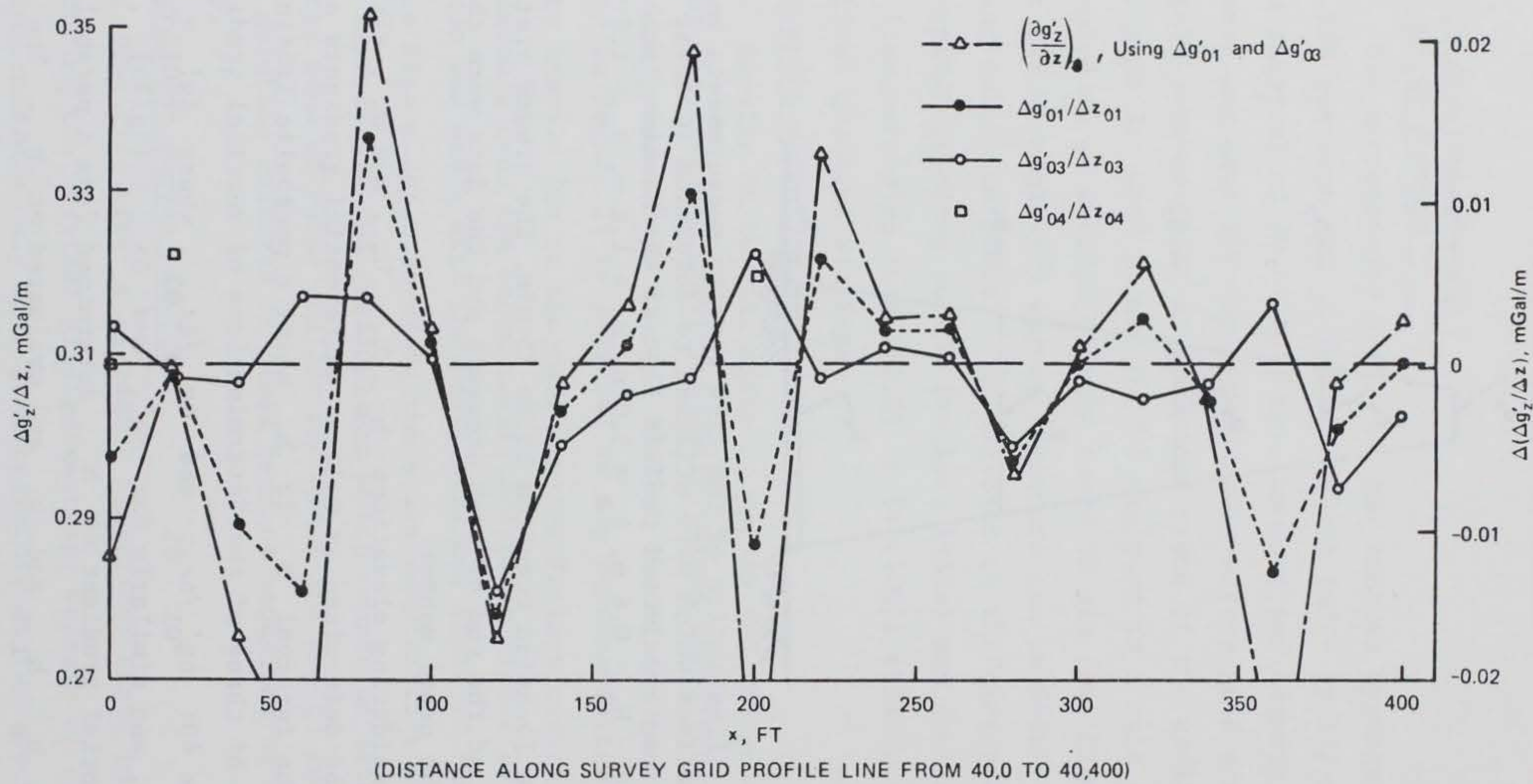


Figure 40. Interval vertical gradients along the (40,0) to (40,400) profile line at the Manatee Springs site

considerable variation, with several gradient anomalies as large as 10 percent of the normal vertical gradient. Generally, the $\Delta g'_{03}/\Delta z_{03}$ profile is smoother than the other profiles as expected, since it should be less affected by very shallow density anomalies. All three profiles behave qualitatively the same except at profile positions 0, 40 to 60, 200, and 360 where the $\Delta g'_{03}/\Delta z_{03}$ profile behavior is clearly at variance with the other two profiles. In many locations the three values are nearly identical; and at the 100- and 300-ft profile positions all four values are nearly equal and also nearly equal to the normal gravity gradient; which implies a linear variation of gravity with elevation at these locations. There is, however, no obvious indication of an anomaly which could be caused by the subsurface cavity system.

Horizontal gradient determinations

80. Using the gravity data along the selected profile line, interval horizontal gradient profiles can be determined using various values of Δx . Clearly, for cases where there is no regional gradient along the profile line, or where the regional gradient is linear in the profile direction, the results will be identical whether the Bouguer anomaly or the residual anomaly values are used to compute horizontal gradient. When the above conditions do not hold, there will be a regional component present in the gradient profile. In the present case, it is preferable to use residual gravity values. Horizontal gradient profiles for Δx equal to 20, 40, and 80 ft (6.1, 12.2, and 24.4 m) are shown in Figure 41, where the residual gravity values from Figure 23 were used. The profiles in Figure 41 clearly become smoother with increasing Δx . Importantly, all three profiles show "average behavior" consistent with the known cavity system with center at profile position 200 ft. The $\Delta x = 20$ -ft profile, however, is so erratic that the "cavity gradient signature" is effectively masked. The gradient "signature" of the cavity is enhanced by Δx values which are larger than the effective depths of the shallow anomalous features causing the erratic behavior of the $\Delta x = 20$ -ft profile. Accordingly, the $\Delta x = 80$ -ft profile data will be used for the considerations which follow.

Comparison of results with two-dimensional model calculations

81. The cavity system was modeled as a two-dimensional, horizontal cylinder with rectangular cross section as shown in Figure 26, and TALGRAD was used to compute horizontal and vertical gravity gradients. In Figure 42, the computed horizontal gradient profile is compared with the measured horizontal gradient profile for $\Delta x = 80$ ft. The average behavior of the measured profile approximates the calculated profile quite well in amplitude and spatial wavelength, with the amplitude of the measured profile slightly larger on the right-hand side. HILBERT was used to compute a vertical gradient profile from the measured horizontal gradient profile for $\Delta x = 80$ ft. This profile, computed by the Hilbert transform procedure, is compared in Figure 43 to the vertical gradient profile computed from the two-dimensional model. Again, the agreement between the two profiles in Figure 43 is good with respect to amplitude and spatial wavelength; however, the Hilbert transform profile has maximum amplitude at position 240 ft rather than 200 ft and has a prominent positive peak at 320 ft.

82. Gradient space plots prepared from the profiles in Figures 42 and 43 are shown in Figure 44 for the two-dimensional model and for data derived from the field measurements. The somewhat subtle differences noted in the profile data plots are more apparent in the gradient space plot; to profile position 200 ft (lower half of plots in Figure 44), the agreement between the two plots is good, but from profile positions 200 to 400 ft (upper half of plots in Figure 44), the two plots differ significantly in magnitude. The results in Figure 44 suggest that the simple two-dimensional model which was selected may not approximate the cavity system very well. Indeed, reports of both a cave diving team and a very limited verification drilling effort confirm that the cavity system is extremely complex. The cavity varies erratically in cross-sectional shape and size; a vaulted ceiling is common and numerous smaller branching cavities are present. Also, drilling indicates more extensive solutioning to the northeast of the (0,200) to (100,200) line than southwest of it, which is consistent with both the residual gravity map and the gravity-gradient results.

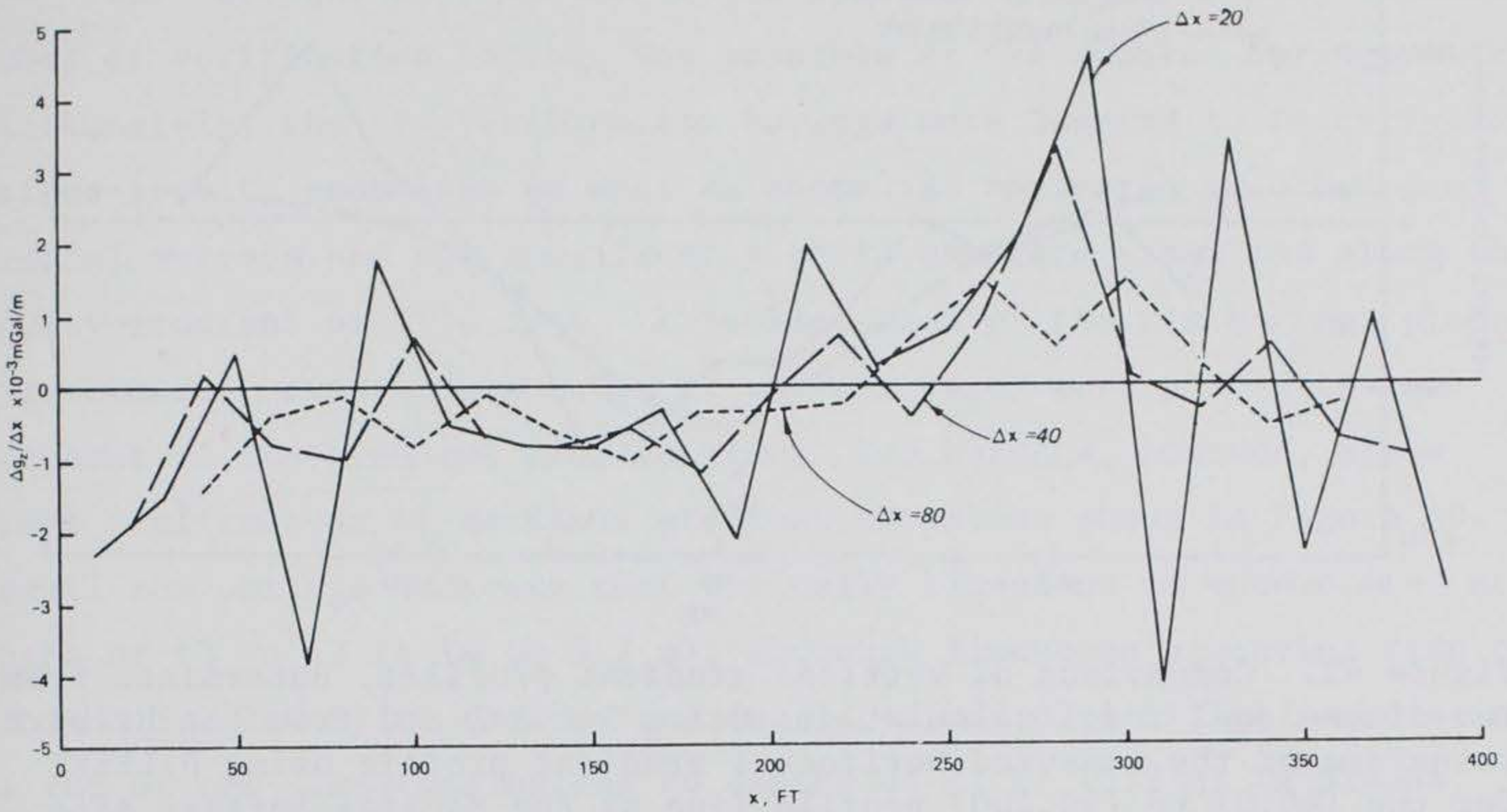


Figure 41. Interval horizontal gradient profiles for three values of Δx along the (40,0) to (40,400) profile line at the Manatee Springs site

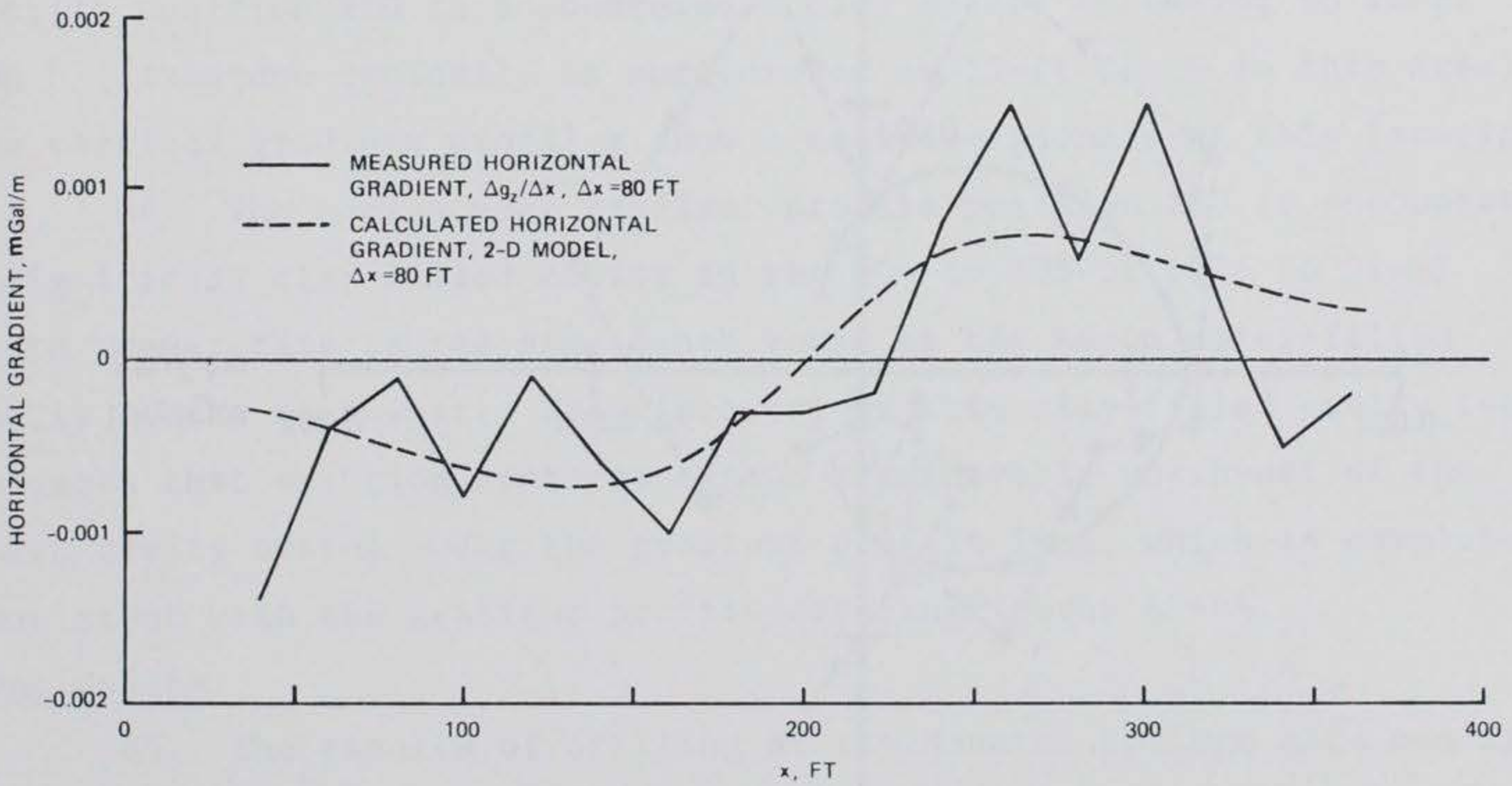


Figure 42. Comparison of measured and calculated (using TALGRAD) interval horizontal gradients along the (40,0) to (40,400) profile line at the Manatee Springs site

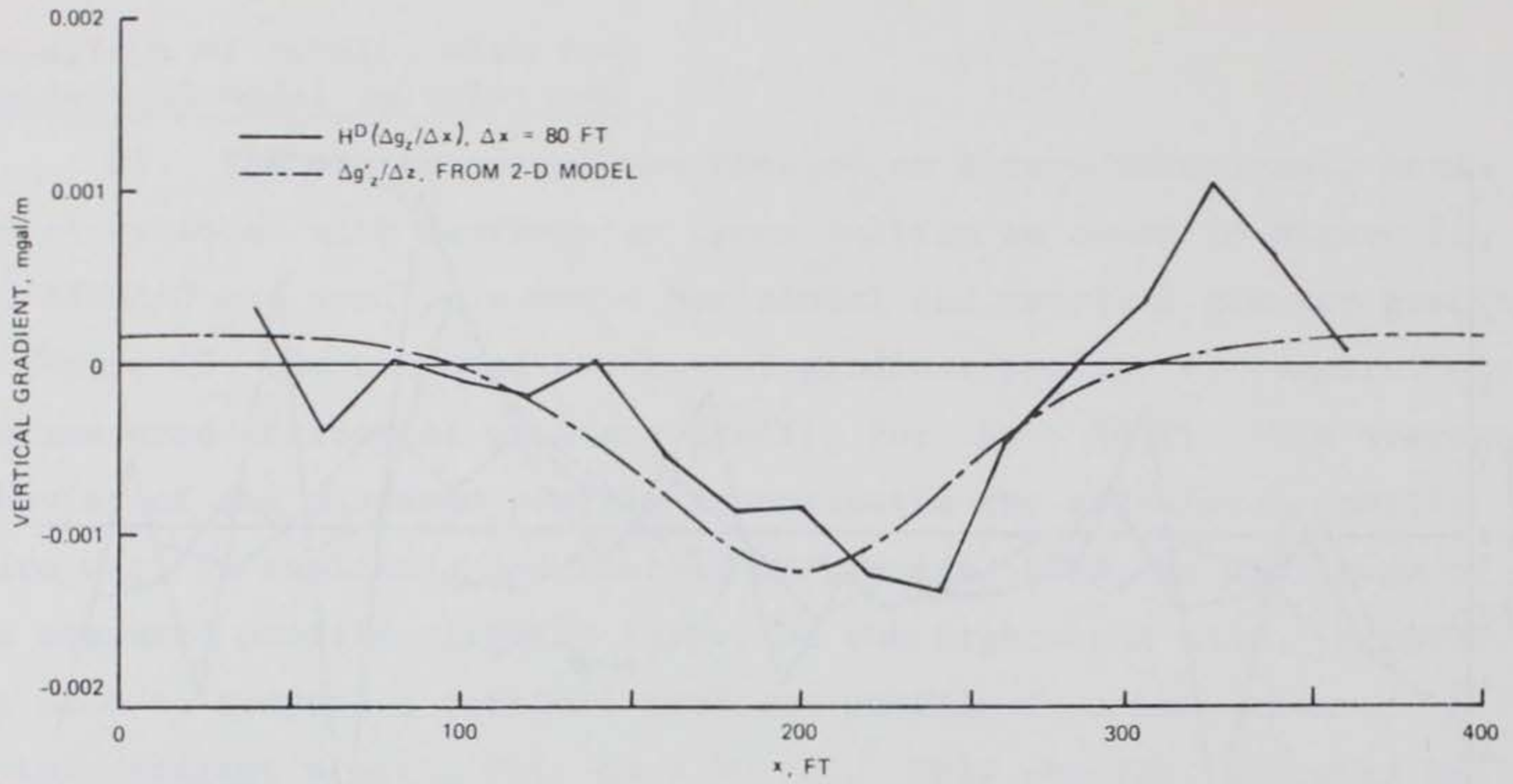


Figure 43. Comparison of vertical gradient profiles, determined from two-dimensional model calculations using TALGRAD and from the Hilbert transform of the measured horizontal gradient profile using HILBERT for the (40,0) to (40,400) profile line at the Manatee Springs site

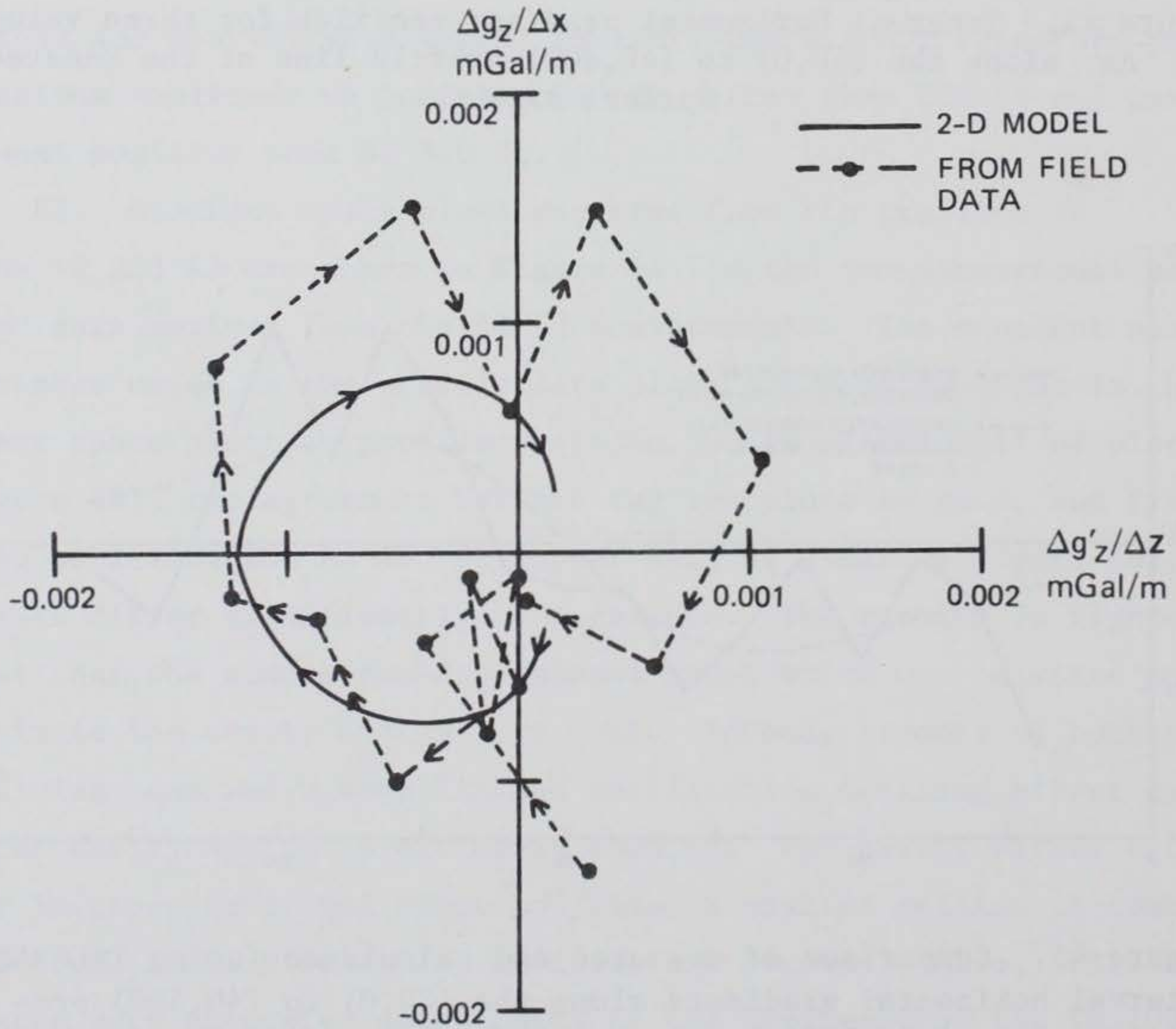


Figure 44. Gradient space plots for gradient data along the (40,0) to (40,400) profile line at the Manatee Springs site

Verification drilling results

83. Because of time and fiscal constraints, only a very limited number of verification borings was possible at the Manatee Springs site. Unfortunately, the six verification borings were located to investigate various gravity anomalies as well as anomalies indicated by other geophysical surveys and not specifically to investigate anomalies along the gravity-gradient profile line. Likewise, most of the six borings placed to accommodate crosshole surveys of various types were placed to the northeast of the gradient profile line. Two borings, however, allow direct confirmation of vertical gradient anomalies shown in Figure 40. Overall the borings indicate that typically limestone is encountered at depths of 13 to 17 ft (4 to 5.2 m), although limestone pinnacles rise to within 5 ft (1.5 m) of the surface in places and clay-filled pockets in the top of the limestone extend to depths of 27 ft (8.2 m) in places. A boring near gradient profile position 120 ft encountered a clay pocket which extended to 27-ft depth (limestone typically is encountered at 17-ft depth in this area); the vertical gradient profiles show a prominent negative anomaly at this location. Another boring near gradient profile position 280 ft encountered a clay pocket extending to 16-ft depth (limestone typically is encountered at 13-ft depth in this area); the vertical gradient profiles show a negative anomaly at this location.

84. The boring near gradient profile position 280 ft encountered a significant clay-filled cavity in the 90- to 105-ft (27- to 32-m) depth range; this is the same depth range as the known water-filled cavity to the southwest. The discovery of this clay-filled cavity feature suggests that solution features extend considerably northeast of the known cavity system under the gradient profile line, which is completely consistent with the gradient profile data in Figures 42-44.

Conclusions

85. The results of drilling at the Manatee Springs site confirm that the larger magnitude, short spatial wavelength anomalies which appear in the measured vertical gradient profiles in Figure 40 are due primarily to relatively shallow (<20 ft or 6 m) density anomalies such as clay pockets and limestone pinnacles. The lower amplitude, longer

spatial wavelength anomalies which appear in the measured horizontal gradient and Hilbert transform vertical gradient profiles in Figures 42 and 43 are due to the deeper (>80 ft or 24 m) main cavity system. The large amplitudes of the vertical gradients caused by shallow feature at the Manatee Springs site completely mask any possible expression in the measured vertical gradient profile of the low amplitude anomaly due to the deeper cavity system, at least in vertical gradient profiles determined with a short, portable tripod. A much taller tower (>20 ft or 6 m in height) with lower measurement station several feet (1 to 2 m) above the ground would be required to have any chance of detecting the vertical gradient anomaly caused by the cavity system; even then, it is unlikely that a 0.001 mGal/m gradient anomaly could ever be detected by a tower (interval) measurement procedure.

Gravity-Gradient Analysis of a Selected Gravity
Profile Across Dry Lake Valley, Nev.

Concepts

86. One of the important and powerful aspects of the gravity-gradient analysis and interpretation procedures (Butler, 1980a, b, c) is that they can be applied to existing good quality gravity data at any scale. Gravity profiles can be digitized; and using the basic digitizing interval as a starting point, horizontal gradient profiles can be computed for various multiples of the basic interval. The Hilbert transform procedure is used to compute vertical gradient profiles, and then the gradient space plot and modulus of the analytic signal plot can be constructed. Implicit in the procedure just described is that the structural aspects of the problem being analyzed are two-dimensional. If a gravity contour map is used as a starting point, gravity profiles should be selected across and approximately perpendicular to the trend of anomalies which in some sense can be considered to be caused by a two-dimensional structure. If the starting point is a gravity profile, it should cross a known structure which can be considered approximately two-dimensional in nature, striking nearly perpendicular to the profile

line. An example of the first of these cases is presented here, i.e., a gravity profile is selected perpendicular to the major trend of an elongated gravity anomaly associated with an alluvial basin in the Basin and Range Province.

Background

87. The Dry Lake Valley gravity survey is briefly discussed earlier in this Part as an example of the use of TALGRAD.

88. Dry Lake Valley is located in central Lincoln County, Nev., approximately 170 km north-northeast of Las Vegas. The gravity survey, consisting of 1069 stations in and around Dry Lake Valley, was conducted by the Defense Mapping Agency (DMA) in the summer of 1977. Correction of the gravity data was performed by DMA and Fugro National, Inc. personnel to produce a Bouguer anomaly map. The regional field was derived by fitting a second-order polynomial surface to Bouguer anomaly values on bedrock outcrop stations around the valley. Subtracting the derived regional field from the Bouguer anomaly map yielded the residual anomaly map shown in Figure 28. Complete details of the site, gravity survey, and data correction procedures are given in Fugro National, Inc. (1980) and McLamore and Walen (1979).

89. Dry Lake Valley exhibits typical basin and range structure, with the valley probably occurring above a graben between two high angle normal basement faults on the east and west sides of the valley. Outcrops in the mountains on the western side of the valley are predominantly Tertiary ash flow tuffs with some Paleozoic carbonates; while the mountains on the eastern side are predominantly the Paleozoic carbonates with only minor amounts of the Tertiary tuffs. The valley fill consists of unconsolidated to partially consolidated silt, sand, and gravel derived from adjacent highlands. Primarily the fill materials are Tertiary and early Quaternary alluvial fan deposits (72 percent by area) and fluvial and stream terrace deposits (16 percent).

90. The three-dimensional model and interpretation discussed previously and shown in Figure 29 were constrained by (a) results of two long intersecting refraction lines in the north end of the valley, (b) several shallow (<500 ft or 150 m) boreholes throughout the central

portion of the valley, and (c) a knowledge of the structural style of the region. A density contrast of -0.45 g/cm^3 (between alluvium and carbonate bedrock) was determined by trial and error gravity interpretation to yield the best "tie" of the refraction results. This density contrast agrees with published density values for bedrock and alluvium materials in the area (McLamore and Walen, 1979). An interesting feature of the interpretation shown in Figure 29 is that the placement of the faults was determined from an examination of the second vertical derivative of the gravity field; i.e., the faults are placed along the zero contour of the second derivative field. This procedure places the surface trace of the eastern boundary fault about 1 mile west of the surface cracks in the alluvium, which have been mapped as a fault.

Gradient interpretation

91. Profile AA' in Figure 29 was chosen for gradient analysis and is plotted in Figure 45.* The gravity profile was digitized at 1-km intervals and horizontal gravity gradients were calculated for $\Delta x = 1$,

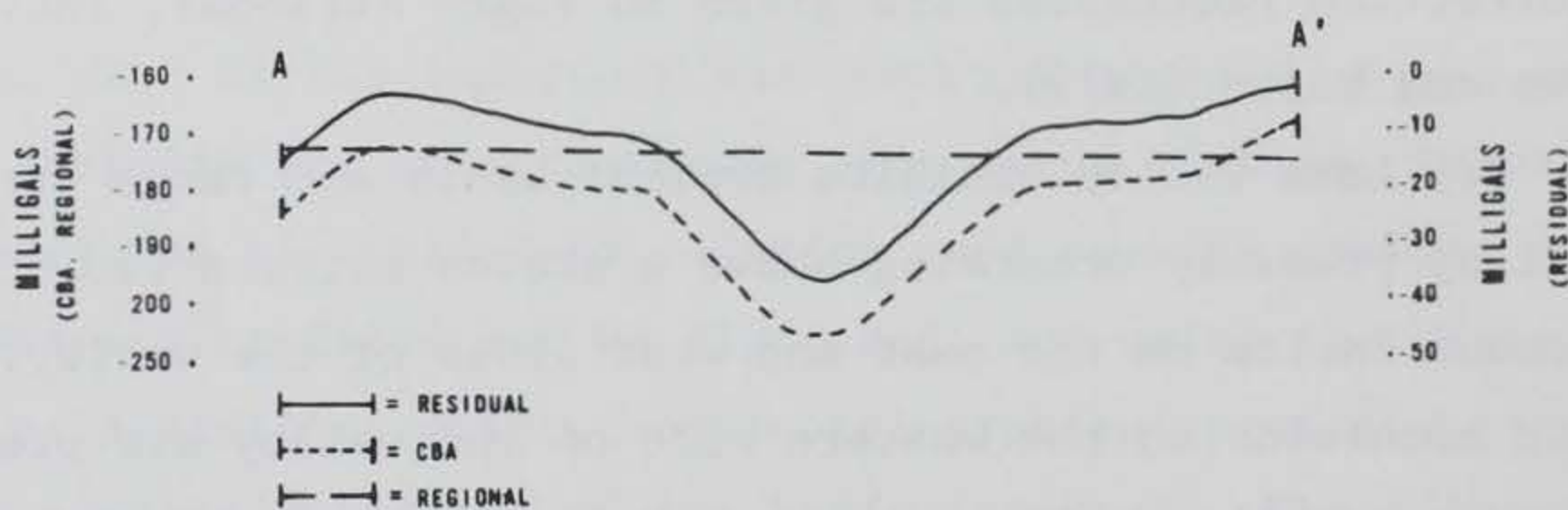


Figure 45. Bouguer anomaly (CBA), regional field, and residual anomaly for Profile AA' (see Figure 28)

2, 3, and 5 km. HILBERT was used to calculate vertical gradients from each of the horizontal gradient profiles, and the gradient profiles for the four cases are shown in Figure 46. The gradient profiles clearly become smoother and exhibit fewer "complexities" as Δx increases due to the filtering properties of the interval measurement procedure; and the gradient profiles for $\Delta x = 5 \text{ m}$ closely resemble those for a

* A much larger version of this gravity profile was used for digitization.

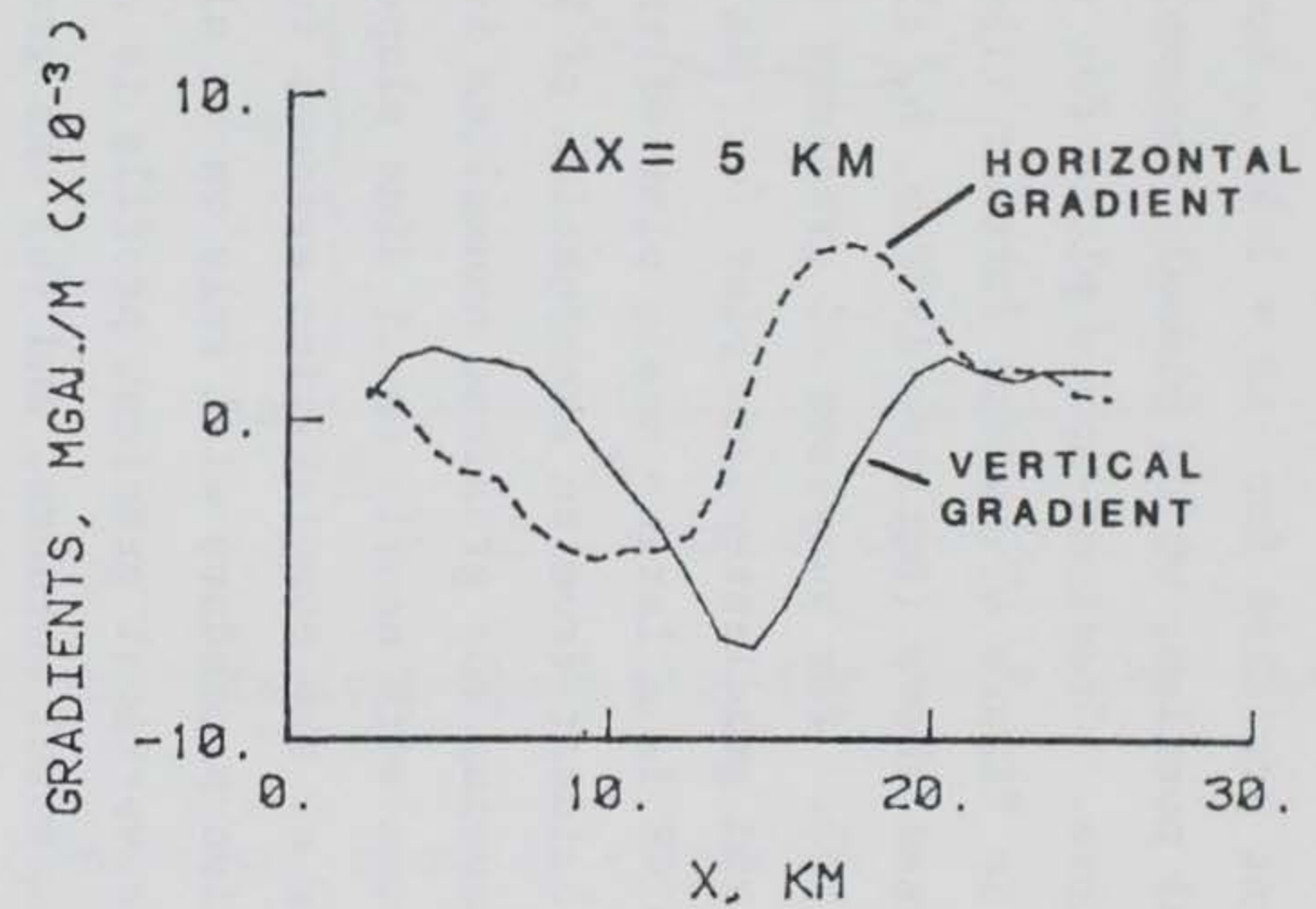
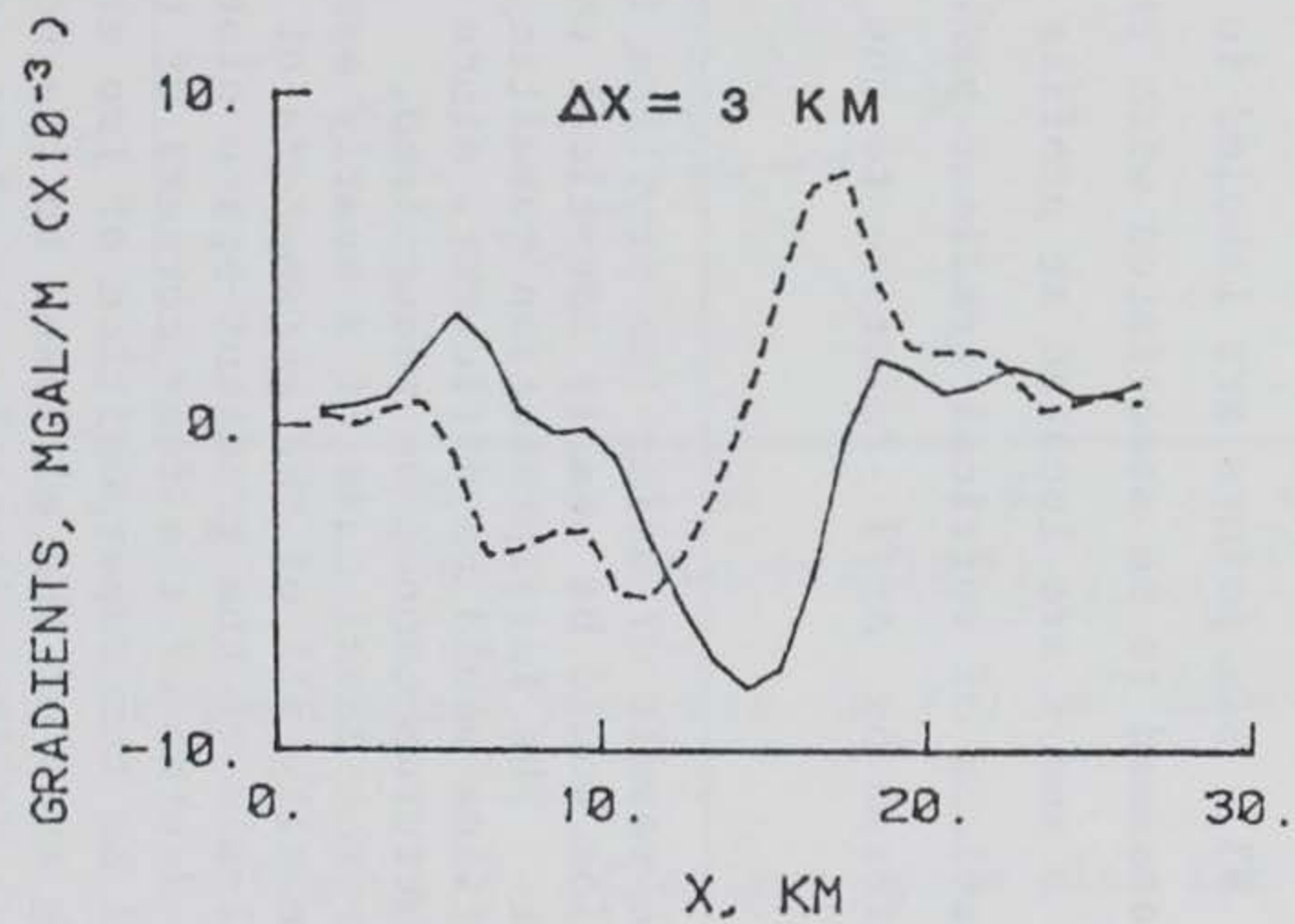
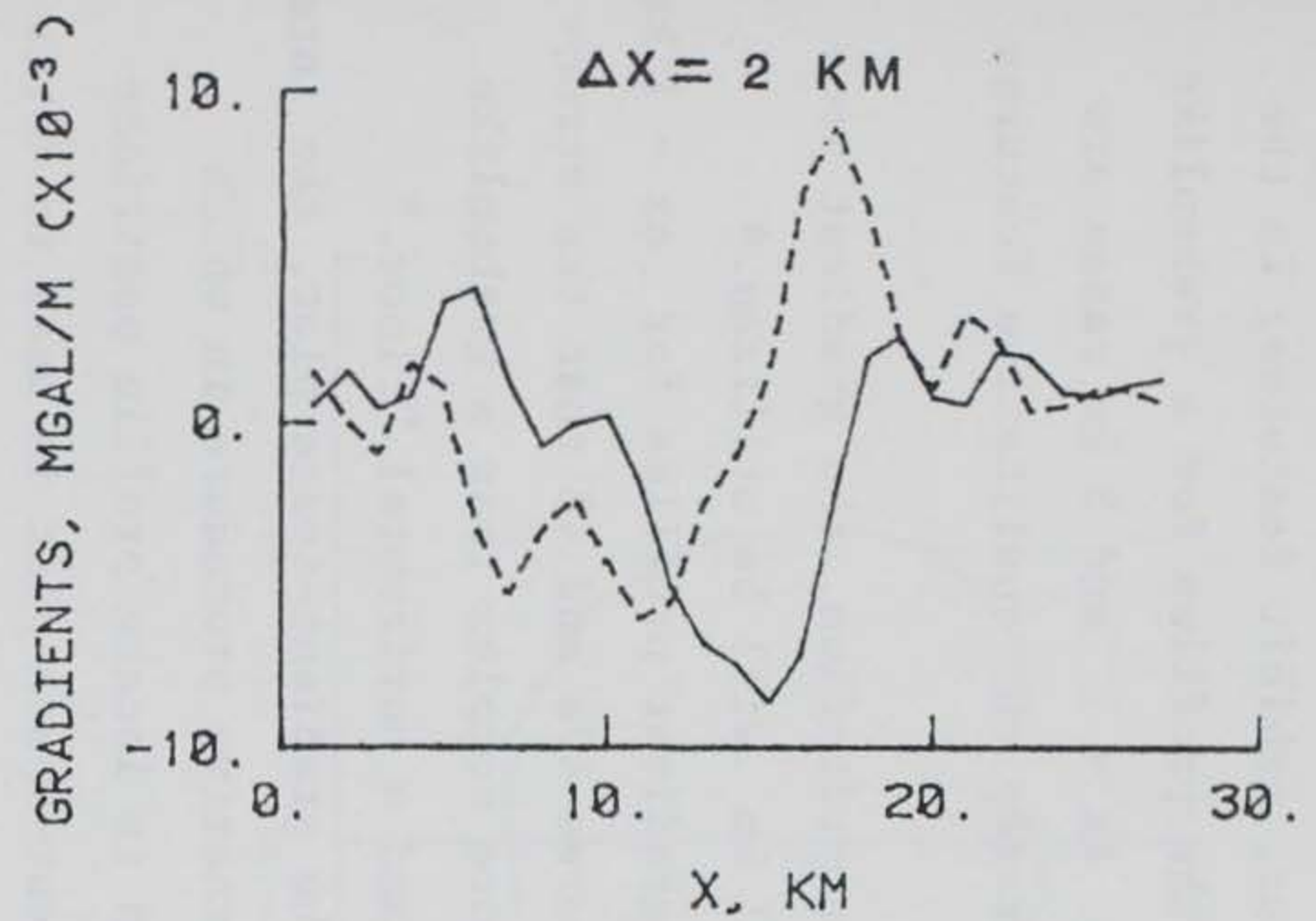
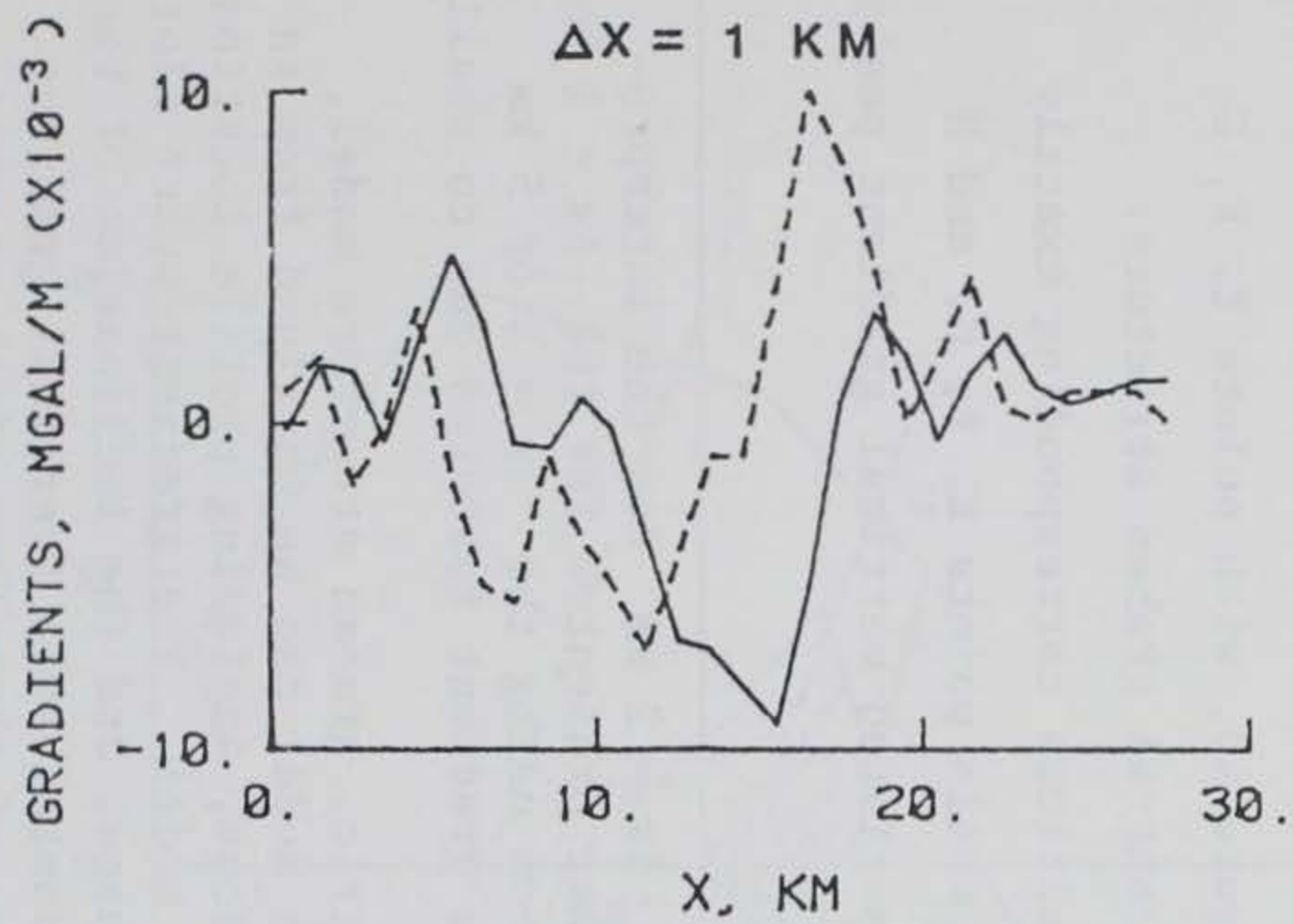


Figure 46. Measured horizontal gradient profiles for four values of Δx and associated computed vertical gradient profiles along AA' (see Figure 28)

horizontal cylinder (the simplest two-dimensional structure). The gradient profiles for $\Delta x = 1$ km, however, exhibit features, in the central portion, which closely resemble the profiles for a grabenlike structure. Gradient-space plots for the $\Delta x = 1$ and 5 km cases are given in Figure 47, which further illustrates the qualitative features discussed above (Butler, 1980 a, b, c).

92. For purposes of gradient interpretation, the gradient profiles and gradient-space plot for $\Delta x = 1$ km will be utilized.* Figure 48 is a larger scale plot of the gradient profiles for $\Delta x = 1$ km. It is evident from an examination of Figures 47a and 48 that the structure causing the gradient anomalies is more complex than a grabenlike structure with nearly equal side slopes and a horizontal "floor." Because of the complexities evident in the gradient-space plot, the interpretation procedure will rely on an alternative procedure in which (a) the vertical gradient profile is used to locate profile positions of structural corners, and (b) the gradient-space plot is used to determine slope angles of the graben bounding-faults and their projected surface intersection points.**

93. Six points are labeled in Figure 48, with points E, F, G, and H assumed to be associated with the central graben structure. Points D and I are located at profile positions corresponding exactly to locations of vertical gradient peaks, while points E, F, G, and H are shifted by $\Delta x/2$ relative to the associated vertical gradient peaks

* The result of using the profiles for $\Delta x = 2$ km for the interpretation would be nearly identical to that presented for the $\Delta x = 1$ km case. The interpretation resulting from using the $\Delta x = 3$ or 5 km profiles would be different, since the gradient features due to shallow structures cannot be recognized.

** For the ideal case of a nearly symmetric, graben structure model, generally all of the parameters of the model can be obtained from an analysis of the gradient-space plot alone, including profile locations and depths of the four corners of the model. The gradient-space plot will be the superposition of two ellipses, and the inclination of the long axes of the ellipses to the horizontal axis (vertical gradient axis) defines directly the slope angles of the sides of the graben model relative to the horizontal.

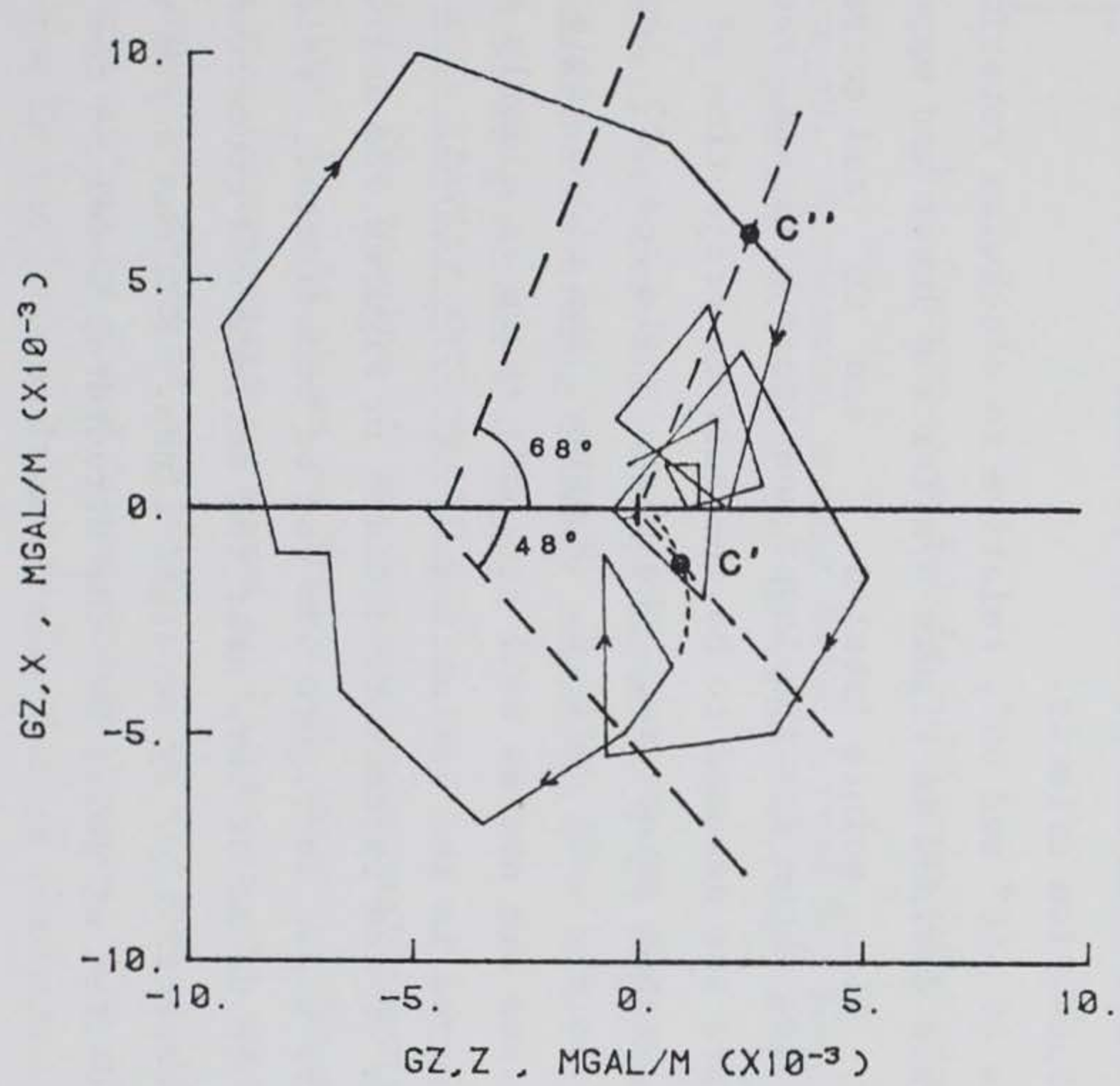
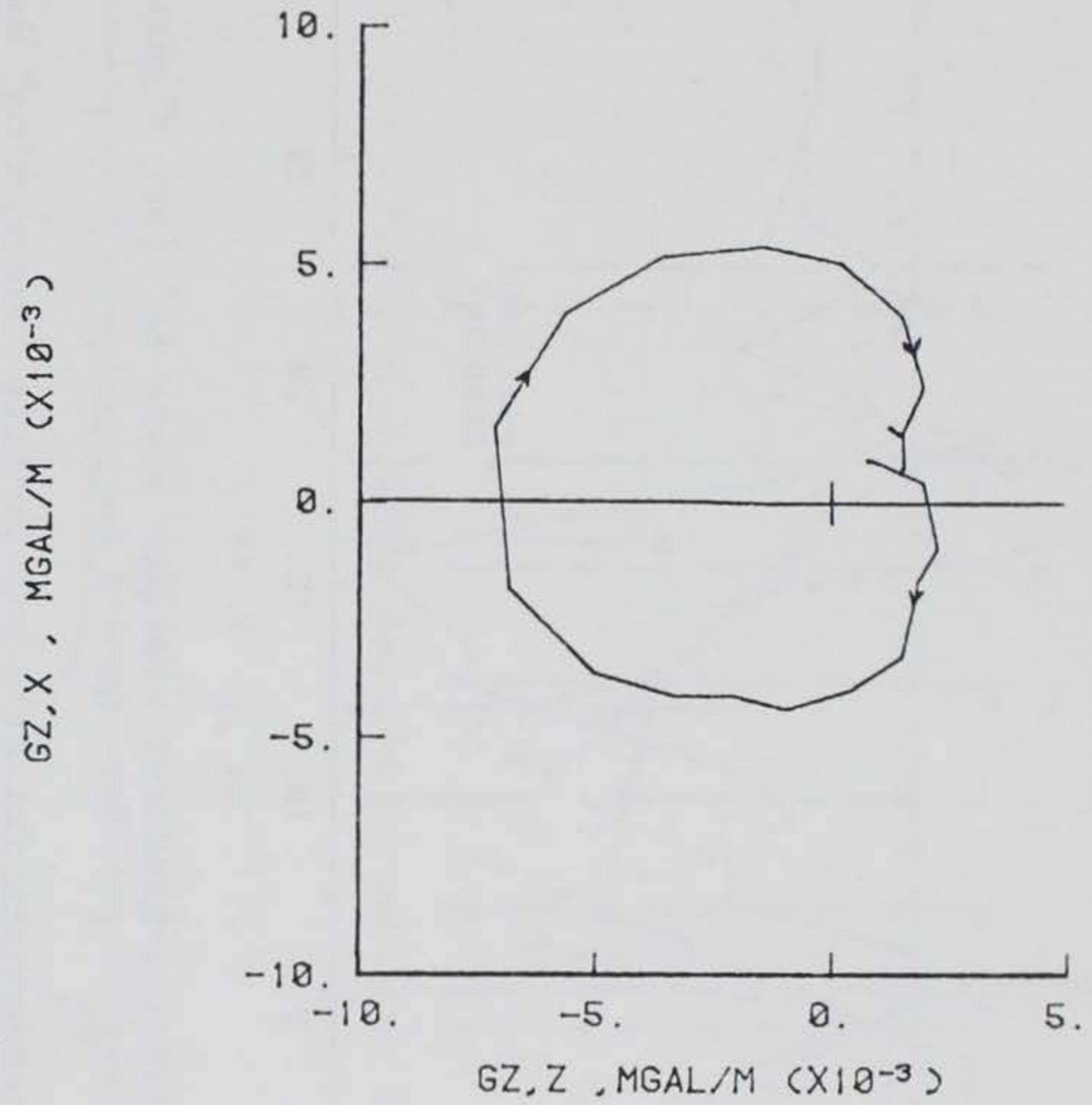
a. Gradient-space plot for $\Delta x = 1$ km caseb. Gradient-space plot for $\Delta x = 5$ km case

Figure 47. Gradient-space plot for two of the cases shown in Figure 26

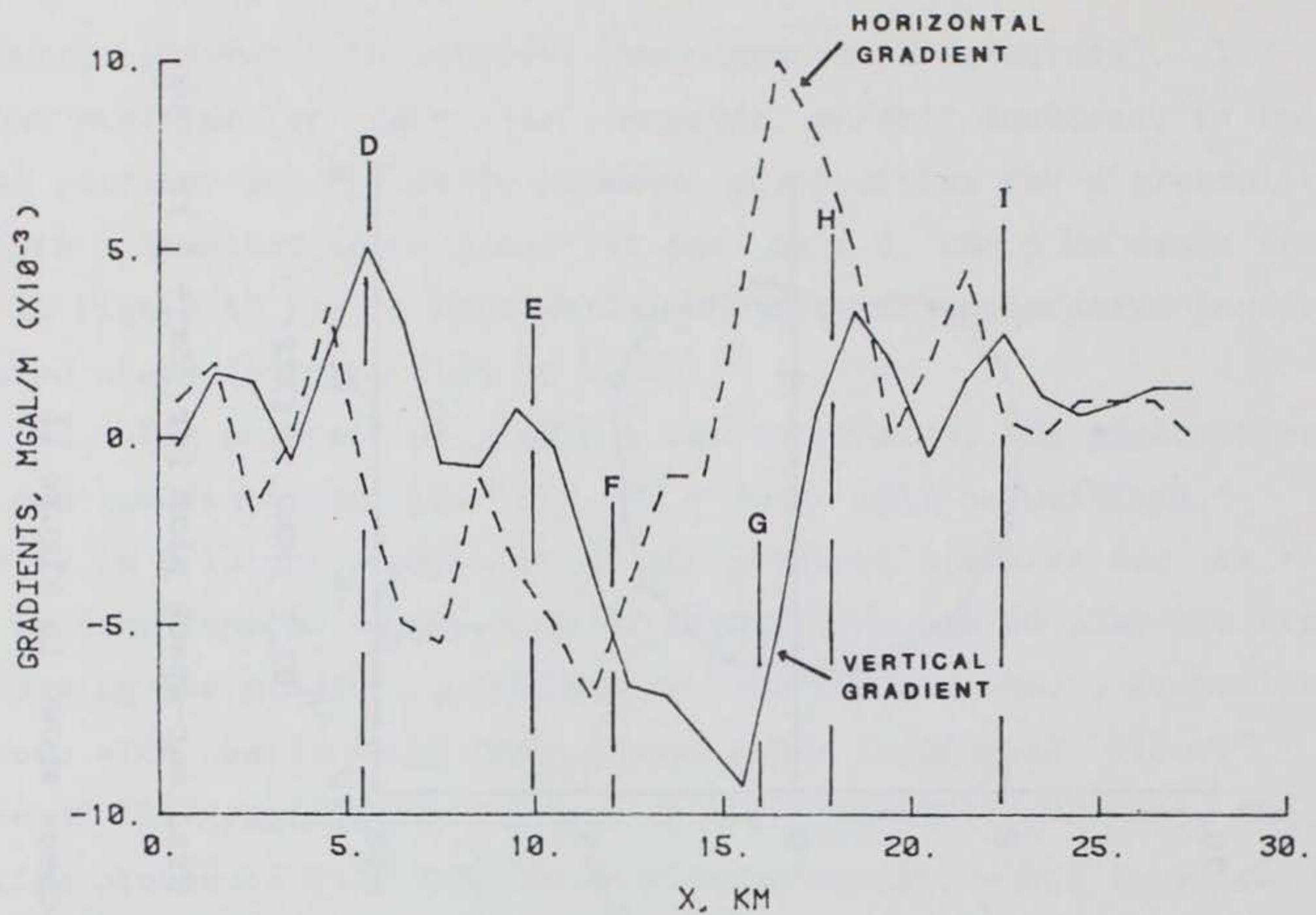
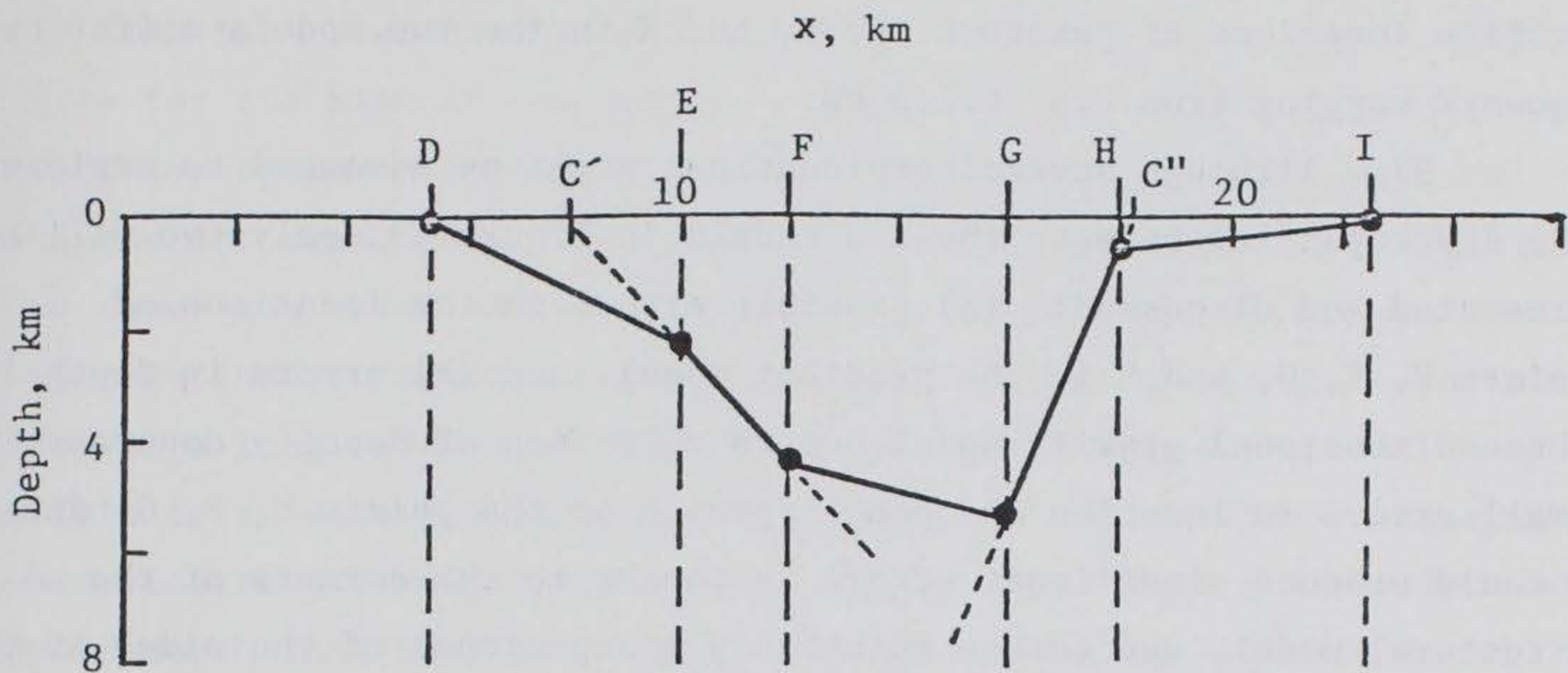


Figure 48. Gravity-gradient profiles along AA' (see Figure 28) for $\Delta x = 1$ km

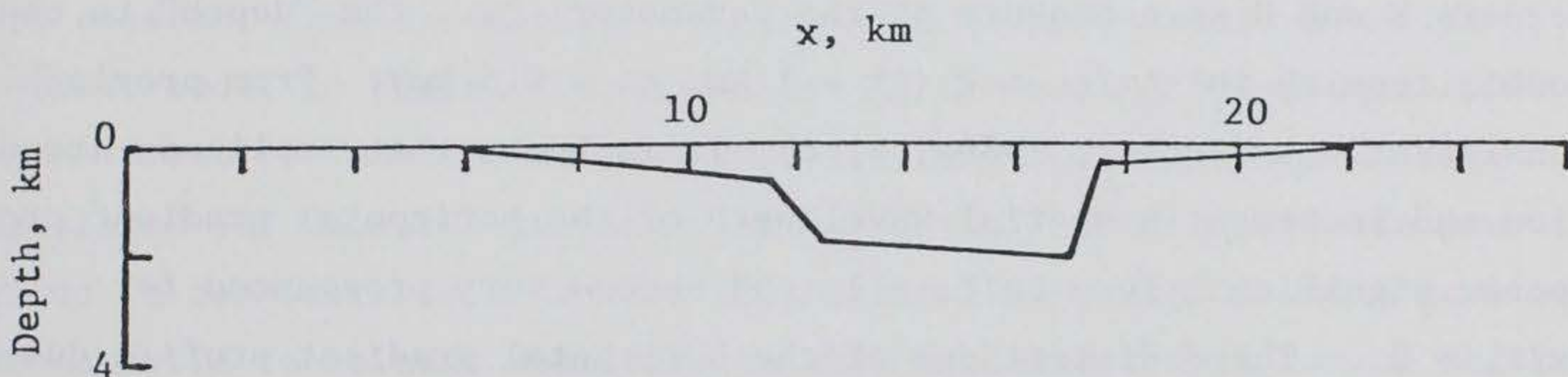
to qualitatively compensate for gradient profile "broadening" due to sampling and superposition effects.

94. Angles of -48° and 68° , relative to clockwise rotations from the $g_{z,z}$ axis, are defined in Figure 47a for the lower and upper ellipses, respectively. Also, points labeled C' and CC' and corresponding profile locations are shown for the lower and upper ellipses, respectively; these points are assumed to be the surface projection of the side faces of the graben structure. The slope angle and C' for the upper ellipse are fairly well defined. However, the slope angle and C' for the lower ellipse are not as well defined; there is clearly subjective judgment involved in the definition of C'.

95. By use of the parameters defined in Figures 47a and 48, the structural geometry shown in Figure 49a can be constructed. Points D and I are assumed to be at or very near the surface and connected to points E and H, respectively, by straight lines. Maximum depth to rock of ~ 5.4 km is predicted at point G. The structural model of the valley



a. Structural model deduced by gradient methods



b. Structure model from 3D gravity inversion

Figure 49. Structural models deduced from Dry Lake Valley gravity profile AA' using two different interpretive methods

fill-bedrock geometry is deduced directly from the gradient data with no assumptions regarding density contrasts.

Comparison of gradient and three-dimensional gravity interpretation

96. The results of the three-dimensional gravity inversion along profile line AA' are shown in Figure 49b (also in Figure 30). Qualitatively, the two interpretations shown in Figure 49 are very similar, and the slope angles of sides EF and GH in Figure 49a and their counterparts in Figure 49b differ by 1 and 5 deg, respectively. The primary quantitative difference is the rather dramatically larger predicted depth to the

carbonate bedrock predicted by the gradient model. Profile locations of points D and I are approximately the same in both models; however, profile locations of points E, F, G, and H in the two models differ by amounts varying from 0.5 to 1.5 km.

97. Although several explanations might be advanced to explain the discrepancies between the two models in Figure 49, only two will be presented and discussed: (a) possible errors in the locations of points E, F, G, and H in the gradient model, and (b) errors in depth in three-dimensional gravity model due to selection of density contrast. Small errors in location and hence spacing of the points E, F, G, and H could produce significant errors in depths to the corners of the structural model, due to the relatively steep slopes of the sides of the graben structure. If the model shown in Figure 49b, from the three-dimensional gravity inversion, is correct, then using the depths to the corners E and H as a measure of the parameter ζ_0 , the "depth" to the model, results in $\Delta x/\zeta_0 \sim 2$ ($\Delta x = 1$ km, $\zeta_0 \sim 0.5$ km). From previous considerations (Butler, 1980a, b, c), it is known that amplitude attenuation and increase in spatial wavelength of the horizontal gradient profile become significant for $\Delta x/\zeta_0 = 1$ and become very pronounced for $\Delta x/\zeta_0 = 2$. These distortions of the horizontal gradient profile due to the sampling process will be reflected in the vertical gradient profile (computed with HILBERT) by increased separation and broadening of the peaks (relative maxima) corresponding to corners E and H, leading to values for the distances EF and GH which are too large. It is noteworthy, however, that the locations of corner H and its surface projection C" for the gradient model in Figure 49a are more consistent with surface cracks in the alluvium than the corresponding locations in Figure 49b.

98. An equally plausible explanation for the differences in the two models in Figure 49 is that the predicted depths in Figure 49b are too small due to the use of a density contrast which was too large (Butler, 1980a). The density contrast of -0.45 g/cm^3 used for the three-dimensional gravity inversion corresponds to the density contrast for shallow sediments relative to basement rocks. Since the sediment density

will increase with depth, -0.45 g/cm^3 must be viewed as a maximum density contrast (Fugro National, Inc., 1980). Thus, the depths calculated from the three-dimensional inversion are likely too small, particularly for the base of the graben. Additional modeling with different density contrasts or a density contrast function that decreases with depth was not considered to be justified by Fugro because so little is known about the actual density distribution in and around the valley. Without further information, such as a deep boring in the center of the valley or a long refraction line in the center of the valley, it is not possible to resolve the discrepancy between the two models in Figure 49. Density contrast considerations seem clearly to favor a valley model with greater depth than in Figure 49b. Since the model in Figure 49a, deduced by gravity-gradient techniques, was produced without assumptions regarding density contrast, it seems to be the preferred model. The best constant density contrast for the valley, corresponding to the gradient model in Figure 49a, could not be determined by using TALGRAD in an iterative fashion, varying only the density contrast until the calculated and measured gravity profiles agree. This example is presented in considerable detail to illustrate the manner in which some of the analytic techniques developed in this research effort can be utilized to analyze field data to determine geologic structure and geophysical properties.

PART IV: SEISMIC METHODS

Background

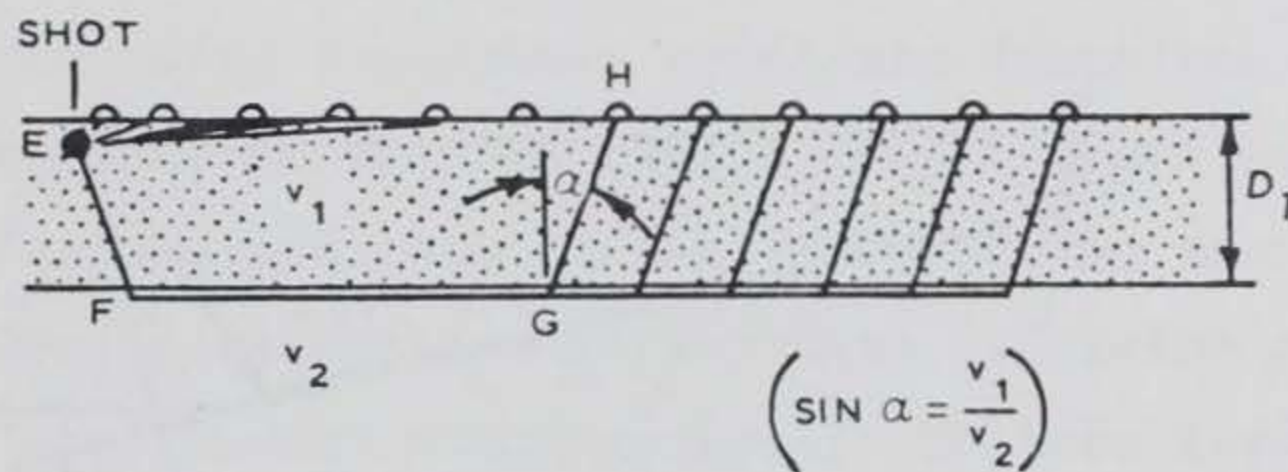
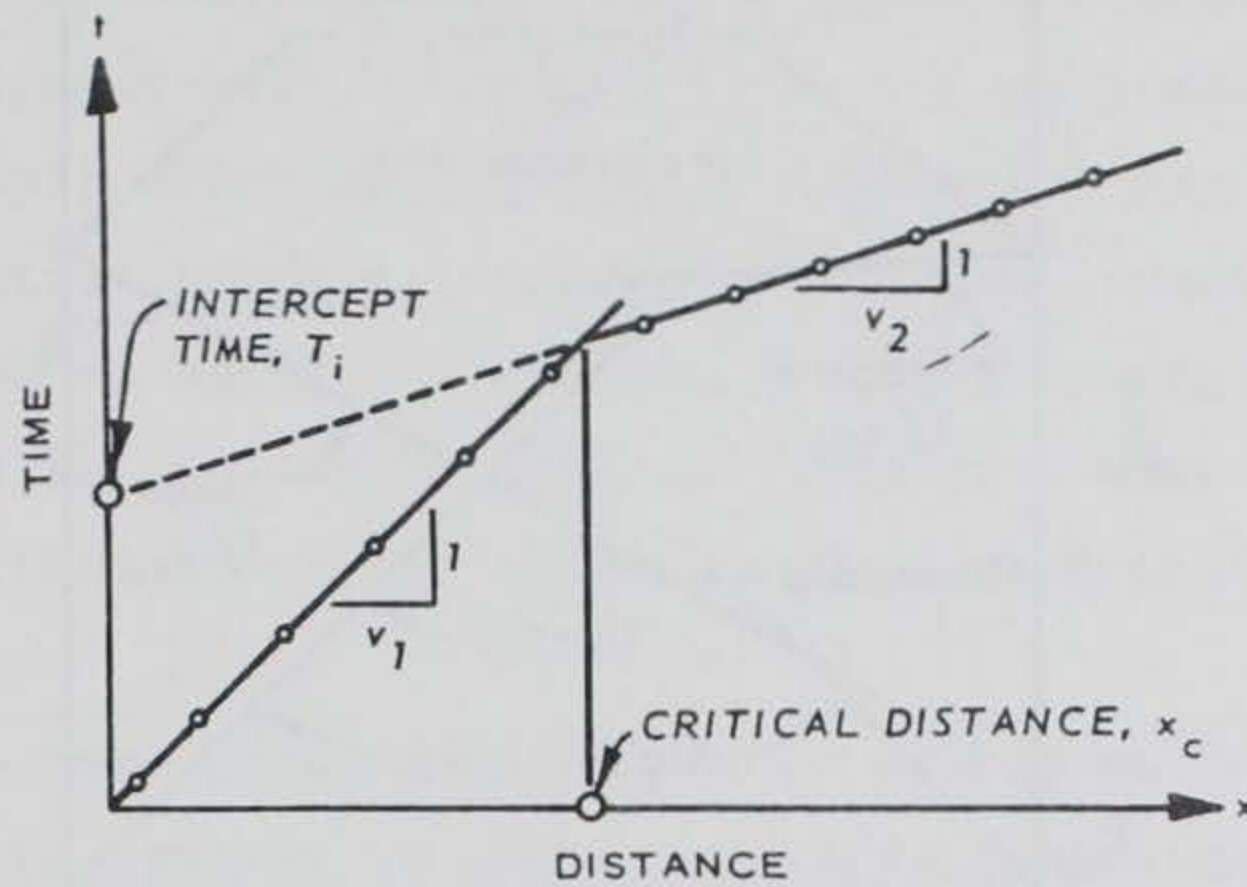
99. The seismic methods all involve the generation, propagation, and detection of seismic waves. Seismic waves are generated in three ways in surveys for geotechnical applications: impact sources, e.g., weight drop or hammer blow; explosive sources, e.g., dynamite, exploding bridgewire (EBW) detonators, and air guns*; and vibratory sources (constant frequency or swept frequency sources). Detection of the seismic waves is generally by velocity transducers called geophones. The objective of the seismic methods is to deduce properties of the media through which the seismic waves pass from properties of the detected wave forms (primarily the arrival times of various events or types of waves at the geophones). Two seismic methods are considered here: the seismic refraction method and the crosshole seismic method.

Seismic refraction method

100. The seismic refraction method is a surface survey technique in which the source locations and geophones are along a common line. Figure 50 illustrates the concept of the seismic refraction method, where the time-distance plot represents the arrival times of the first event at each geophone location. The first event at a given geophone will be due to a wave which propagates directly from the source or to a wave which is refracted along an interface with a higher velocity material. The first-arrival time-distance plot can be analyzed to give the velocities of subsurface soil/rock layers and depths to interfaces; Figure 50 illustrates the analysis for the simple case of two horizontal layers (Department of the Army, 1979).

101. For the case of three horizontal layers, the analysis of the time-distance plot to yield layer velocities and interface depths is still tractable by manual methods. Also, the case of two layers where the interface dips relative to the surface can be similarly analyzed

* Air guns generate seismic waves by a sudden release of compressed gas.



$$\left(\sin \alpha = \frac{v_1}{v_2} \right)$$

$$D_1 = \frac{x_c}{2} \sqrt{\frac{v_2 - v_1}{v_2 + v_1}}$$

Figure 50. Simple two-layer case with plane, parallel boundaries, and corresponding time-distance curve (after Redpath, 1973)

using manual methods (Department of the Army, 1979; and Telford et al., 1976). However, for the cases of greater than three horizontal layers and greater than two dipping layers, a programmable calculator or a minicomputer is desirable for the interpretation. The presence of dipping layers is indicated by an examination of the time-distance plots from forward and reverse "shooting" along a seismic survey line, i.e., from data obtained by using a source at each end of the geophone line.

Figure 51 illustrates the appearance of the time-distance plot for a two-layer case with dipping interface, where the apparent velocity of the second layer is always greater when "shooting" in the updip direction.

102. In the past, seismic refraction data processing has involved manual "picking" of first-arrival events and scaling arrival times, often

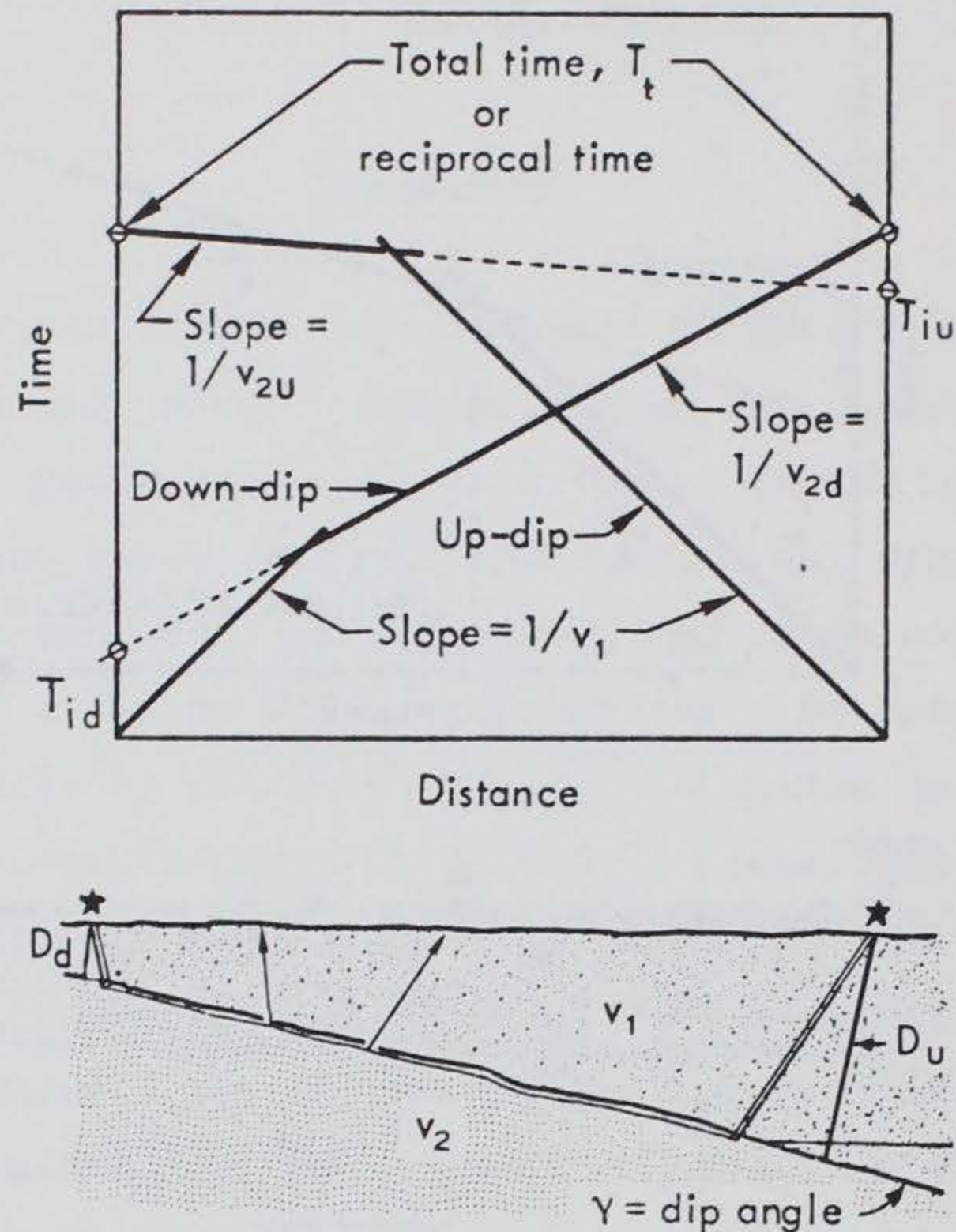


Figure 51. Example of dipping interface and concepts of "reverse shooting" and "apparent velocity" (after Redpath, 1973)

using a variable scale, from analog records. The time-distance data were then manually plotted, and straightline segments were fit to the data if possible. Velocities were then determined as the inverse of the slopes of the line segments. Interface depths and dips were then determined manually. This is still a common procedure, particularly when refraction survey data are processed and interpreted in the field.

103. Magnetic tape (analog) data recording has been used since the early 1950's and digital tape data recording since the early 1960's in seismic exploration for the oil industry. Associated with the digital seismic recording capability has been a rapid growth in digital data processing technology. This new technology makes possible the expeditious handling of enormous amounts of seismic data and reduces complex mathematical filtering operations to simple multiplications and additions of the digital data. Although many of the digital techniques which have been developed are applicable to any set of time series

data, the primary application has been to seismic reflection survey data. Also, equipment cost, physical size, and complexity of operation have prevented application of digital recording and processing technology to seismic refraction surveys for geotechnical applications. However, since the mid-1970's, small, relatively inexpensive digital seismic recording systems and powerful micro/minicomputers have been developed which can be utilized by groups involved in geotechnical applications of seismic methods.

104. This Part documents techniques developed to expedite seismic refraction data processing and to aid interpretation of seismic refraction results using minicomputers and time-sharing computer systems. While the data processing techniques which are described here must be considered an intermediate step in that analog field records are still utilized, the procedure has considerably reduced the manual effort involved in processing refraction survey data and helps prevent the data processing "bottleneck" which generally follows large field seismic investigations.

Crosshole seismic method

105. The crosshole seismic method utilizes seismic wave propagation between two or more boreholes to determine the seismic stratigraphy, i.e., the seismic velocities of subsurface materials and the locations of interfaces between materials with different velocities in site investigation programs. This method is used extensively in foundation investigations where both compression (P) and shear (S) wave velocities are required as input to dynamic analyses. Field procedures, equipment, and interpretation procedures for crosshole seismic testing are described in Department of the Army (1979), Butler and Curro (1981), and Butler, Skoglund, and Landers (1978).

106. Figure 52 (Butler and Curro, 1981) illustrates the geometry and concept of a crosshole seismic test. A seismic source and receiver are shown at the same depth in a pair of boreholes. The seismic source can be selected to preferentially generate vertically (horizontally) polarized S-wave energy if desired, and vertical-axis (horizontal-axis) receivers (perhaps in a triaxial geophone array) may be used to enhance

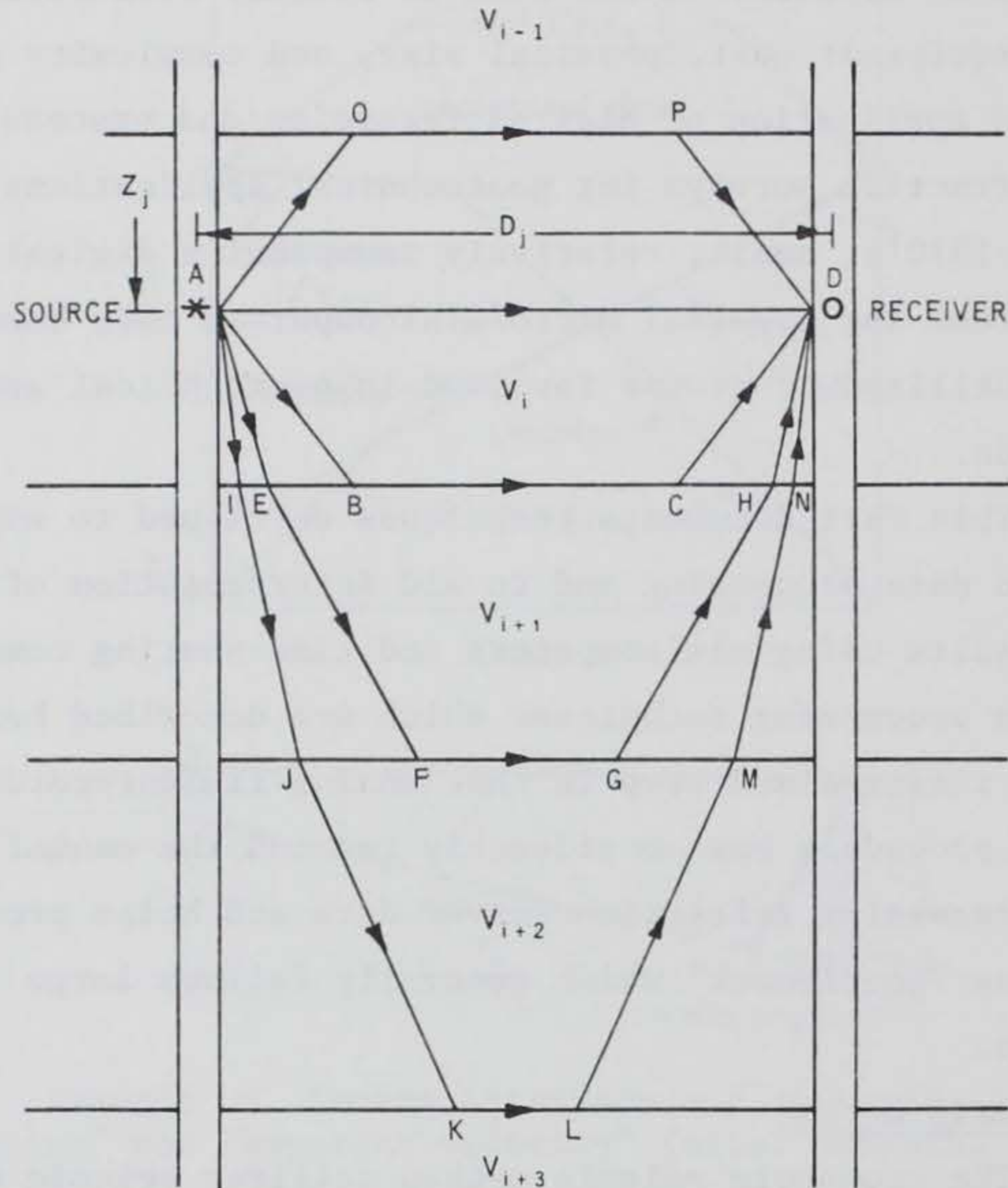


Figure 52. Crosshole seismic test geometry and possible propagation paths

S-wave detection. Explosive sources are rich in P-wave energy, and triaxial geophone arrays or even hydrophones (in fluid-filled boreholes) can be used as receivers for P-wave detection. Figure 52 indicates several layers with different seismic velocities (V_i) and thicknesses; the problem in crosshole seismic interpretation is to deduce this seismic stratigraphy from a data set which includes source/receiver depths and arrival times of events. Generally only the first-arrival times of P- or S-events are considered. The first P- or S-arrival at a given depth Z may be due to any one of the possible paths shown in Figure 52. The first-arrival event will be determined by the borehole separation D , and the magnitudes of the velocities. Dividing D by

the first-arrival time gives an apparent velocity which may not be equal to any of the layer velocities.

107. Butler and Cutto (1981) discuss some of the procedures and pitfalls involved in crosshole seismic interpretation, and Butler, Skoglund, and Landers (1978) present an algorithm and document a computer program (CROSSHOLE) for interpretation of crosshole seismic data. The program CROSSHOLE has been used extensively for the interpretation of crosshole seismic surveys. The program in its original form was somewhat cumbersome to use. Since it was written to be executed in a batch mode on a large computer, a data card deck had to be prepared and submitted for each set of crosshole data. This Part documents the conversion of CROSSHOLE to a time-sharing mode, making the program much more convenient to use and greatly decreasing the turnaround time.

Minicomputer Processing of Seismic Refraction Data

108. In this section, a processing procedure is described in which seismic refraction analog field records are processed by mini-computer. The procedure can be summarized as follows:

- a. The analog records are examined in order to "pick" first-arrival events.
- b. The analog records are placed on a large graphics tablet and the arrival times are digitized using a four-button graphics cursor.
- c. The arrival time-distance data are listed in tabular form and are automatically stored in data files.
- d. Arrival time-distance plots are automatically plotted if desired.
- e. Straightline segments are manually fit to the data on the arrival time-distance plots.
- f. Key points determined by intersections of the straight-line segments are digitized using the graphics cursor.
- g. Velocities (the inverse slopes of the line segments) and depths to interfaces are automatically calculated.
- h. The procedure in steps a-d can be applied to any events which can be identified on the analog records.

BASIC-language programs for accomplishing the above processing steps have been written and are operational on a Tektronix Model 4051 mini-computer and associated digital plotter and graphics tablet; the procedure could easily be adapted for use with other minicomputers with BASIC-language capability. Input instructions for the processing programs follow and listings are given in Appendix H. It is important to note that the key steps in the operation (selecting of first arrivals (step a) and fitting line segments to the data (step e)) are still performed manually. Algorithms have not been developed to replace the judgment involved in these steps.

SEISDIG

109. SEISDIG is a general purpose seismic record digitization program. The program is well documented and prompting messages are printed before each input. The following items summarize the input/output sequence:

- a. The first input request is for data identification, up to 72 characters in length.
- b. The next four input requests are for (1) "shothole" coordinate, (2) distance from "shothole" to nearest geophone, (3) "shothole" depth (zero if source applied at surface, such as hammer blow), and (4) spacing between geophones along survey line.
- c. Three input requests define the time scale: (1) digitize timing line just before time break, (2) digitize timing line 200 msec later (can be changed), and (3) digitize time break (times (1) and (3) can be the same).
- d. Now the first arrivals are digitized using the four-button cursor as follows:
 - (1) Press button "z" to digitize point.
 - (2) Press button "1" to skip a trace.
 - (3) Press button "2" to redigitize last point.
 - (4) Press button "3" to digitize the last point of a record.
 - (5) A tabular listing of arrival time-distance is produced.
 - (6) An opportunity is now given to redigitize any of the points.

(7) The data are now stored in a data file on tape.

SEISPLOT

110. SEISPLOT reads the SEISDIG data files and produces time-distance plots. The program is well documented and prompting messages appear before each input. The following items describe the input/output sequence:

- a. For each operation in the program, the following "menu" is printed, and selection of an item number executes the indicated operation:
 - (1) Enter data.
 - (2) Change or add data.
 - (3) Plot data and label axes.
 - (4) Choose between paper or CRT plot.
 - (5) Display data.
 - (6) Select symbol.
 - (7) Store data on tape.
 - (8) Read data from tape.
 - (9) Stop program.
- b. If menu item (8) is selected, the number of the input data file is requested.
- c. When menu item (3) is selected, x and y scale factors and axis labels are requested, and a plot is produced with x and y axes of 7 in. and 5 in. length, respectively.

REFINT

111. REFINT computes apparent velocities of line segments on the arrival time-distance plot from graphics cursor input of the intersection points of the line segments. Also, assuming the apparent velocities are true layer velocities, interface depths are calculated. If both forward and reverse time-distance plots are analyzed, true layer velocities are calculated using the harmonic mean formula.* The following items summarize the input/output sequence:

* i.e., $\frac{1}{V_T} = \frac{1}{2} \left(\frac{1}{V_F} + \frac{1}{V_R} \right)$; where V_T refers to true velocity, and V_F and V_R are the forward and reverse velocities, respectively;
 $V_T = V_F = V_R$ if the refractor is horizontal.

- a. The first two input requests establish whether or not both forward and reverse data are to be processed, and, if so, which is to be input first.
- b. The next three inputs are with the graphics cursor and establish the scale factors: origin, rightmost point on horizontal axis, uppermost point on vertical axis.
- c. Next, the number of velocity layers associated with the forward and reverse data is input.
- d. The crossover (critical) distances or line intersection points plus an additional point on the highest velocity line are now input with the cursor.
- e. Next, a series of inputs establishes the geometry of the line, including source locations relative to the origin and source depths.
- f. The tabulated output includes the critical distances, apparent velocities, and calculated depths (assuming horizontal refractors) for forward and reverse survey lines and finally the true velocities.

Example 1

112. Figure 53 is an example of the plotted output of SEISPLOT. The data are from a single-ended seismic refraction line. Triangles in Figure 53 represent first-arrival events at the 24 geophones of the line, and the source* point is at the origin. The survey consisted of a series of these single-ended refraction lines along a survey line parallel to a critical structure, with the source point advanced 50 ft each time. The hexagons in Figure 53 are the critical distances or intersection points at A and B and the additional point C on the highest velocity segment which are digitized as input to REFINT. Figure 54 is the tabular output from REFINT.

Example 2

113. Figures 55 and 56 illustrate an example similar to the one above. The objective of this survey was to evaluate a borehole air-gun as a source for seismic refraction surveys. The refracting interface in this case is the water table, and the depth to the interface of 11 ft calculated by REFINT (Figure 56) agrees with the known depth to the water table at the site.

* The source for this survey was a vertically mounted "shotgun" which fires a slug into the ground.

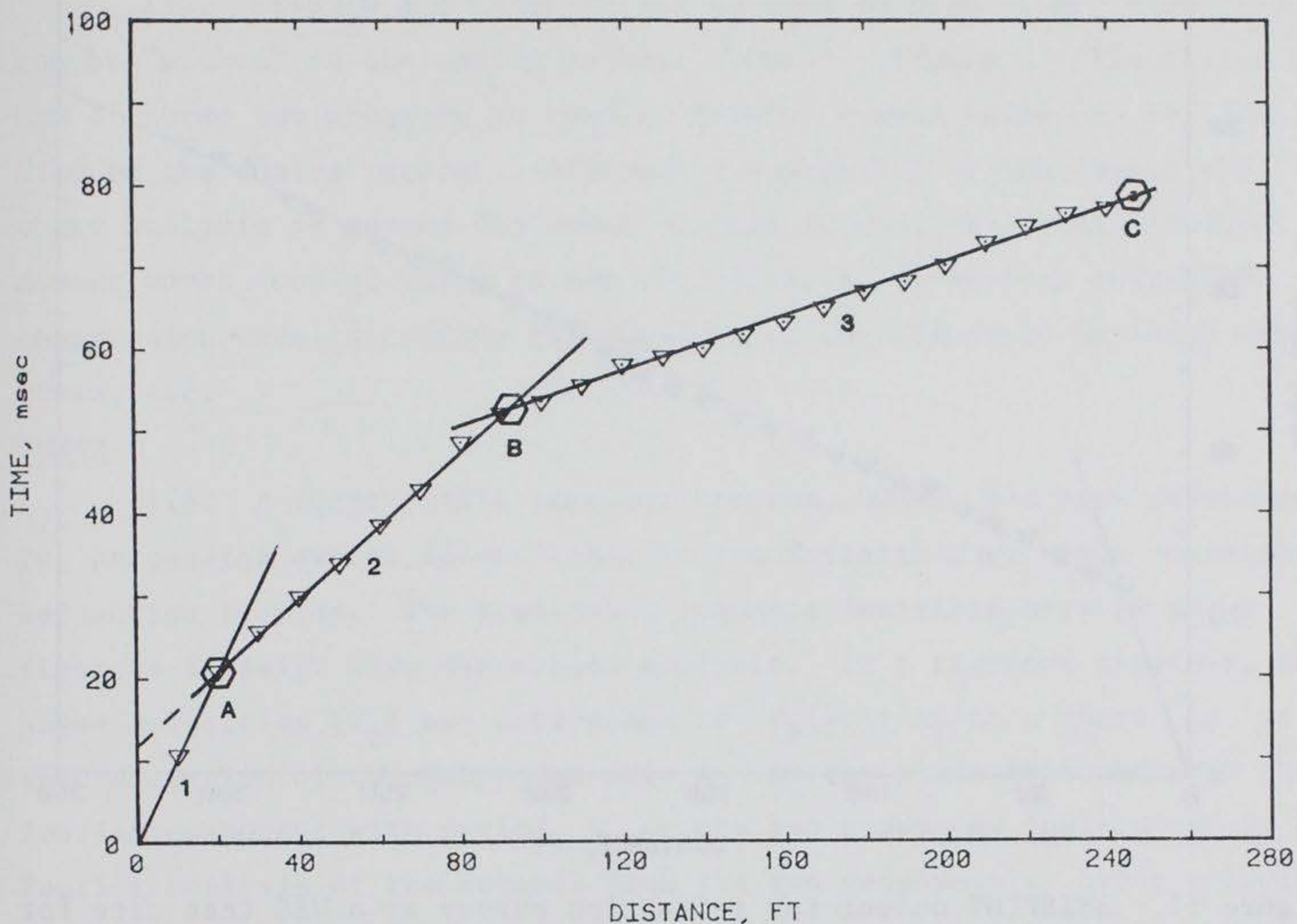


Figure 53. SEISPLOTT output for single-ended seismic refraction line

FORWARD

REVERSE

THE CRITICAL DISTANCES ARE:

X(1) = 20
X(2) = 93

X(1) = 0
X(2) = 0

THE APPARENT VELOCITIES ARE:

U(1) = 948 fps
U(2) = 2295 fps
U(3) = 6091 fps

U(1) = 0 fps
U(2) = 0 fps
U(3) = 0 fps

THE CALCULATED DEPTHS ARE:

D(1) = 6.48 ft
D(2) = 36.55 ft

D(1) = 0.00 ft
D(2) = 0.00 ft

THE TRUE VELOCITIES WERE NOT COMPUTED FOR THIS CASE

Figure 54. REFINT output for the time-distance plot in Figure 53

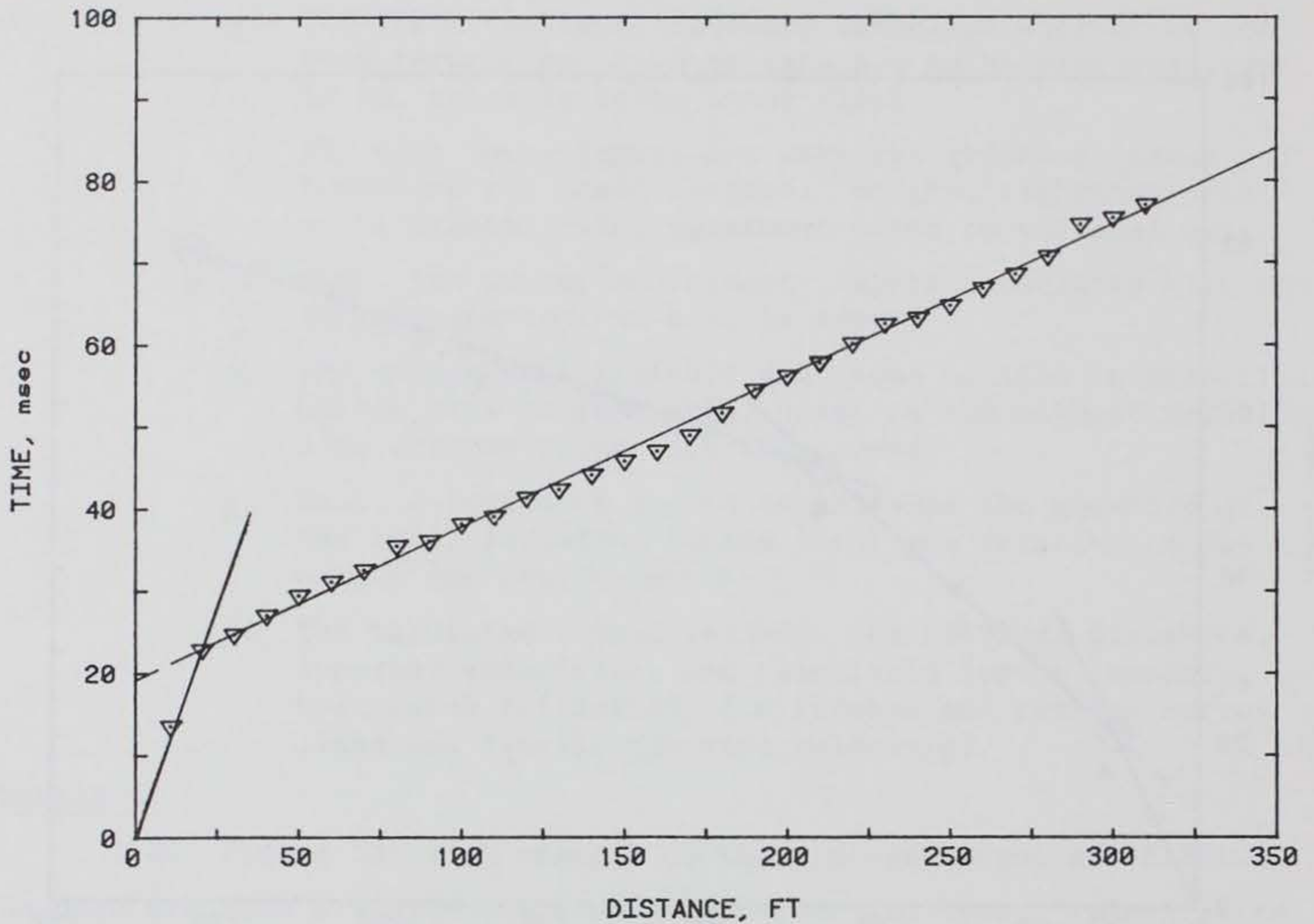


Figure 55. SEISPLOTT output for refraction survey at a WES test site for evaluation of a borehole air-gun source

AIRGUN ON THE WES TEST SITE @ 1000 PSI

FORWARD

REVERSE

THE CRITICAL DISTANCES ARE:

X(1) = 21

X(1) = 0

THE APPARENT VELOCITIES ARE:

U(1) = 909 fps

U(1) = 0 fps

U(2) = 5397 fps

U(2) = 0 fps

THE CALCULATED DEPTHS ARE:

D(1) = 10.98 ft

D(1) = 0.00 ft

THE TRUE VELOCITIES WERE NOT COMPUTED FOR THIS CASE

Figure 56. REFINT output for case shown in Figure 55

Example 3

114. SEISDIG and SEISPLOTT can be used to process any event which can be "picked" on the analog seismic records. Figure 57 illustrates the use of these two programs to process several events which can be identified on the analog records. Although a discussion of the events and their analysis is beyond the scope of this report, the events include direct waves (one of which is the air wave), first-arrival refracted compression wave, secondary refracted wave, the dispersed Rayleigh wave train, etc.

DOMER

115. A fourth BASIC-language program, DOMER, has been developed for processing events identifiable in the Rayleigh wave train on seismic refraction records. The processing sequence described here is not a rigorous Rayleigh wave dispersion analysis. In a rigorous analysis, the phase velocities (V_p) are determined as $V_p(T) = \Delta x / \Delta t$, where Δx is the separation of two geophones and Δt is the phase shift between the Fourier component with period T at the two geophones (determined by a Fourier analysis of the records from the two geophones). Group velocities (V_G) can then be calculated from the phase velocities using the dispersion relation: $V_G(T) = V_p(T) + T[dV_p(T)/dT]$. Plotting group and/or phase velocities as a function of period T or frequency $f(f = \frac{1}{T})$ yields the Rayleigh wave dispersion curves. Interpretation of a dispersion curve involves deducing a layered earth model with a theoretical dispersion curve that best matches the measured curve either with an iterative computer program or a set of standard dispersion curves (Grant and West, 1965); Dobrin, Simon, and Lawrence, 1951; and Ewing, Jardetzky, and Press, 1957).

116. The technique used here is to characterize an identifiable peak or trough in the Rayleigh wave train by its mean period, \bar{T} , which is determined simply as the time difference between the two neighboring troughs or peaks, respectively. If the distance x from the source to a given geophone is greater than the longest wavelength recorded by that geophone, then the group velocity for a period $T = \bar{T}$ is given by $C(T) = x/t$, with sufficient accuracy for most purposes, where t is

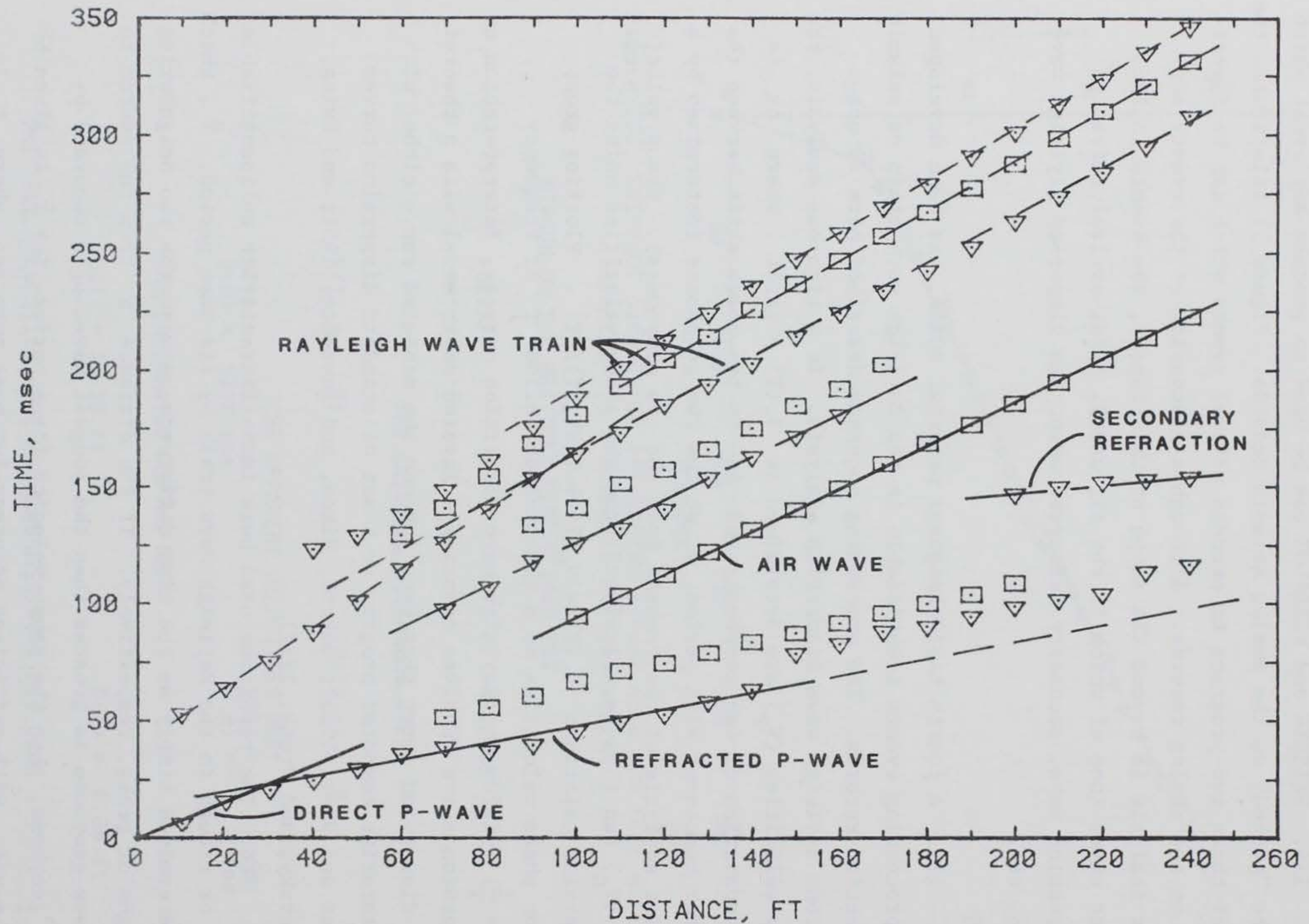


Figure 57. Example of the use of SEISDIG and SEISPLIT to produce time-distance plots for multiple events identifiable on a seismic refraction record

the arrival time for the peak or trough with mean period \bar{T} at the geophone at distance x . For an event, peak or trough, in the Rayleigh wave train that can be followed or identified on two or more geophone traces, the phase velocity can be identified as the inverse slope of a line through the events in a time-distance plot (see Figure 57) if the mean period of the event does not change significantly from one trace to the next (Grant and West, 1965). This technique, particularly the phase velocity determination, is seldom accurate enough for quantitative Rayleigh wave dispersion analysis. Also, it is often not possible to identify enough "events" to define the dispersion curves very well. However, the technique is useful for site characterization, such as location of areas with anomalously low Rayleigh wave velocity (hence, low shear wave velocity). The Rayleigh wave phase velocity versus mean period data can be converted to velocity versus depth data by computing wavelengths $\lambda (=V_p\bar{T})$ and using a "rule-of-thumb," such as the half-wavelength rule, to assign the velocity $V_p(\lambda)$ to a depth $\lambda/2$ (Chang and Ballard, 1973).*

117. A listing of DOMER is in Appendix H, and the input/output sequence is described below:

- a. Input the desired title.
- b. Input the geophone spacing.
- c. Input the time interval to be digitized, e.g., 300 msec.
- d. Digitize, using the cursor, the time interval, e.g., the 0- and 300-msec timing lines.
- e. Digitize zero time, i.e., either the 0-msec timing line or a time-break.
- f. Input the number of events (maximum of five) to be digitized.
- g. For each event:
 - (1) Input starting trace number.
 - (2) Digitize the arrival time of the event, peak, or trough on the starting trace.

* This is only an empirical procedure which should work best for sites where property variations are transitional in nature over the depth of investigation, i.e., not distinctly layered.

- (3) Digitize peak or trough to left of event.
 - (4) Digitize peak or trough to right of event.
 - (5) Move to next trace and repeat steps.
 - (6) One button on the cursor is used for each of the following functions: (a) digitize point, (b) skip a trace, (c) redigitize preceding point, and (d) digitize the last point in an event.
 - (7) Repeat steps (1)-(6) for next event.
- h. For each event a table is printed listing distance (X), arrival time (T), mean frequency (F), and group velocity ($V_g = X/T$) for each peak or trough in that event.
 - i. A time-distance plot for all the events is produced; the input is the same as for SEISPLOT, menu item (3).

Example 4

118. Figure 58 is a plot produced by DOMER of three events identified on a seismic refraction record from the same site as for the examples in Figures 53 and 57. Phase velocities for the events are indicated in Figure 58. Tabular output for event I is given in Figure 59.

Computer Modeling and Interpretation of Seismic Refraction Data

119. Two problems can be identified related to the seismic refraction method: (a) the direct problem, and (b) the inverse problem. The direct problem involves the determination of arrival times as a function of distance from a hypothetical source for various seismic events and a specified model; the model consists of layer velocities, layer thicknesses, and interface dips. For a given set of arrival time versus distance data from a refraction survey, the inverse problem involves the determination of the parameters of a subsurface model from the data itself. Two FORTRAN computer programs have been developed which solve the direct and inverse problems of the seismic refraction method, REFRDIR and REFRINV, respectively. REFRDIR is useful as a modeling tool for planning field surveys, e.g., geophone spacing and

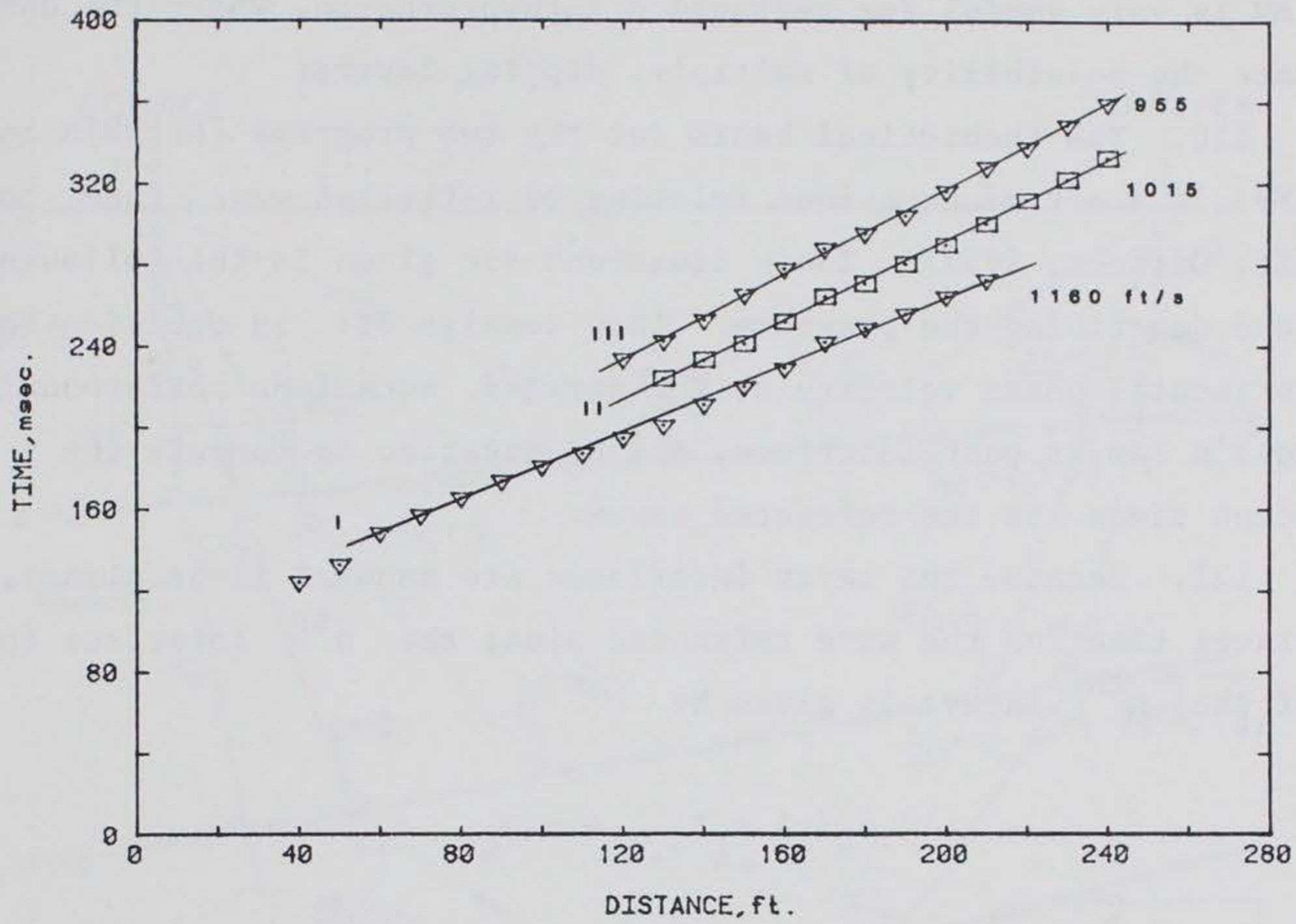


Figure 58. Plotted output from DOMER for three events identified in the Rayleigh wave train on a seismic refraction record

EVENT NUMBER 1

X, ft	T, msec	F, hz	Ug, ft/s
10			
20			
30			
40	124.3	48.1	321.8
50	132.7	49.9	376.7
60	148.5	57.7	404
70	157.2	56.9	445.2
80	165.6	48.7	483
90	174	48.7	517.2
100	181.2	40.8	551.8
110	187.6	39.6	586.3
120	195.3	38.8	614.4
130	201.4	38.5	645.4
140	211.6	40	661.6
150	220.2	40.8	681.1
160	229.4	47.5	697.4
170	242.5	44.9	701
180	249.4	43	721.7
190	256.3	39.2	741.3
200	265	38.5	754.7
210	273.1	37.1	768.9
220			
230			
240			

Figure 59. Tabular output from DOMER for Event I in Figure 58

survey line length required to investigate a possible subsurface model. REFRINV is very useful for refraction interpretation, where the data indicate the possibility of multiple, dipping layers.

120. The theoretical basis for the two programs (REFRDIR and REFRINV) is a set of equations relating to refracted waves (see, for example, Officer, 1957). These equations are given in the following sections describing the programs. They consist of: an equation for the horizontal phase velocity at the surface, equations corresponding to Snell's law at each interface, and an equation to compute the intercept times for the refracted waves.

121. Because the layer interfaces are assumed to be planar, the travel time for the wave refracted along the n^{th} interface (or top of the n^{th} layer) is given by

$$t_n(x) = T_{o,n} + x/v_n \quad (14)$$

Thus, given the horizontal phase velocity, v_n , and the intercept time, $T_{o,n}$ for the n^{th} refraction, the travel time can be computed at all source-to-receiver distances, x .

REFRDIR

122. The horizontal phase velocity and the intercept time are computed for each refraction event using the program REFRDIR. In this case, the P-wave velocities, the interface dips, and the layer "thicknesses" must be given. This program gives the intercept times and the horizontal phase velocities for both the direct and the reverse profile. The reverse profile is that array layout in which the shot is on the opposite end of the array relative to the direct profile.

123. In computing the intercept times and the horizontal phase velocities, program REFRDIR uses the angles, θ_{in}^+ , that the rays make with the normals to the interface. These angles, as well as other important parameters (for example, the layer "thicknesses"), are illustrated in Figure 60.

124. REFRDIR is a modeling program. It assumes: (a) that the velocity variation in the earth increases monotonically with depth,

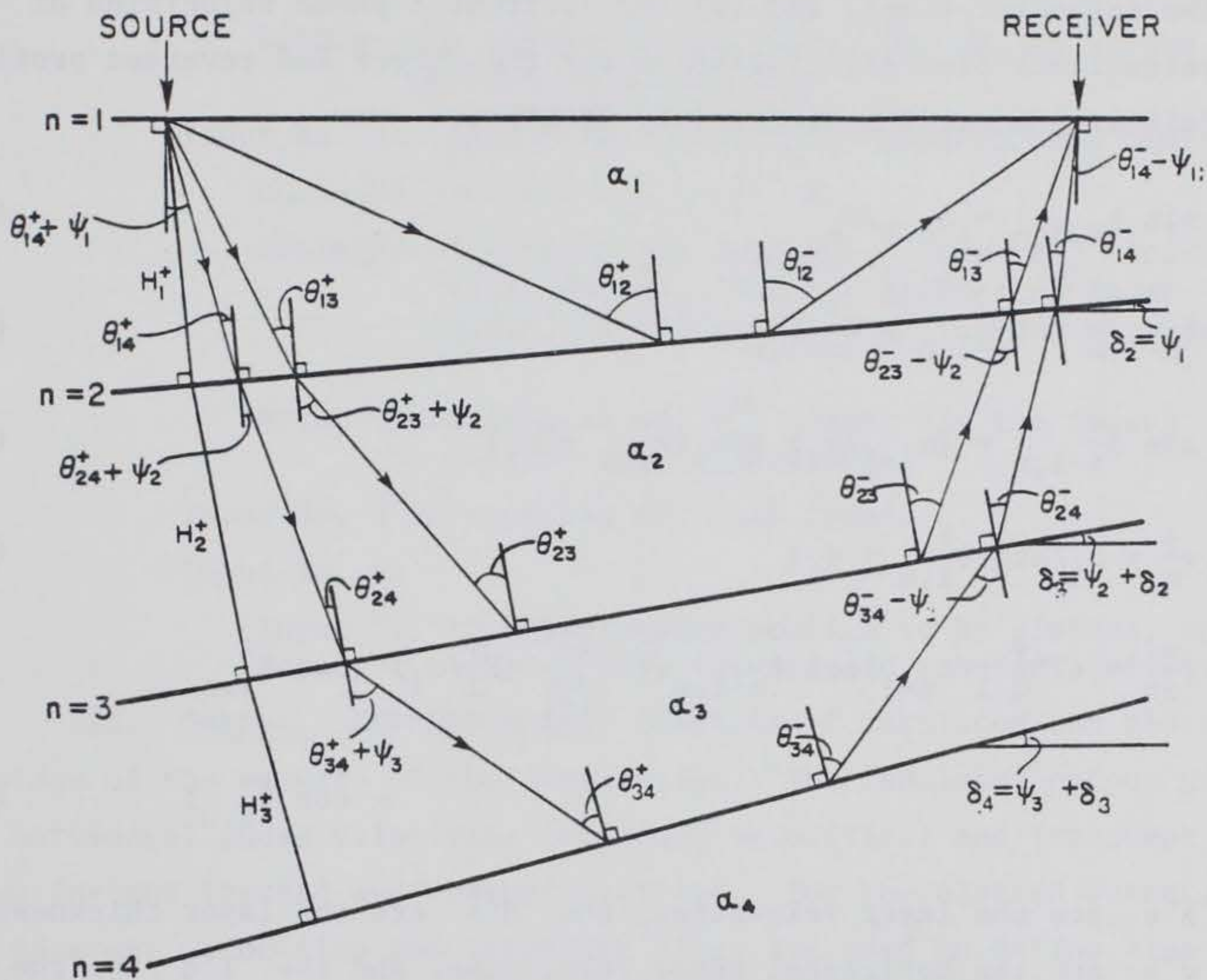


Figure 60. Assumed geometry for seismic refraction paths in common-strike, multiple dipping layers

(b) that it can be approximated by layers of constant velocity but with varying thicknesses, (c) that the interfaces between the layers are planar, and (d) that the interfaces have the same strike (see Figure 60). If REFRDIR is given an input model containing a velocity inversion (i.e., a decrease in velocity with depth), it will print an error message to that effect and stop.

125. The input data for the program are: (a) the number of layers in the model, (b) the layer thicknesses relative to the direct- and reverse-profile shotpoints (HPLUS and HMINUS; see Figure 1), and (c) the dip angles of the interfaces. The air/ground interface is the first one and it is assumed to be horizontal. Any velocity and distance

units may be used, as long as they are consistent, but the (dip) angles must always be given in degrees. REFRDIR computes and prints out: (a) the intercept times, and (b) the horizontal phase velocities of the refractions from each interface for the direct and reversed profiles. The following equations are used by REFRDIR:

$$\sin \theta_{n-1,n} = \alpha_{n-1} / \alpha_n \quad (15)$$

$$\theta_{n-1,n} = \theta_{n-1,n}^+ = \theta_{n-1,n}^- \quad (16)$$

$$\sin \theta_{i-1,n}^+ = (\alpha_{i-1} / \alpha_i) \sin (\theta_{i,n}^+ \pm \psi_i) \quad (17)$$

$$v_n^+ = \alpha_1 / \sin (\theta_{1,n}^+ \pm \psi_1) \quad (18)$$

$$T_{on}^+ = (2H_{n-1}^+ / \alpha_{n-1}) \cos \theta_{n-1,n} + \sum_{i=1}^{n-2} (H_i^+ / \alpha_i) (\cos \theta_{i,n}^+ + \cos \theta_{i,n}^-) \quad (19)$$

The α 's are the layer velocities, the H 's are the layer thicknesses, the v 's are the horizontal phase velocities, and the T 's are the intercept times. The superscripts $+$ or $-$ refer to the direct and reversed profiles, respectively. See Figure 60 for the indexing and angle definitions.

126. For a given layer, computation is started by using Equation 15 to solve for $\sin \theta_{n-1,n}$. This, in turn, is used in Equation 17 to generate $\sin \theta_{n-2,n}^+$ through $\sin \theta_{1,n}^+$. The phase velocities and intercept times are then computed using Equations 18 and 19. To clarify the use of these equations, the calculations for the general case of three interfaces have been carried out in Appendix I. A listing of REFRDIR is also given in Appendix I.

127. Input. REFRDIR is extensively documented and prompting messages appear before each input. All input is in free-field format. The input sequence is given below:

Input No. 1: NLAYRS

NLAYRS--numbers of layers in the model

Input No. 2: SPRDLN

SPRDLN--the spread length, i.e., the length of the refraction survey line

Input No. 3: (ALPHA(N), DELTA(N), HPLUS(N), N=1, NLAYRS)

ALPHA(N)--velocity in layer N

DELTA(N)--dip angle (in degrees) of the N^{th} interface, which is the top surface of layer N ;
DELTA (1) = dip of ground surface of model = 0

HPLUS(N)--thickness of N^{th} layer for the direct profile (see Figure 60)

Input No. 3 is repeated for each layer.

Input No. 4:

Input "1" if only forward profile to be plotted, and input "2" to plot both forward and reverse profiles.

128. Output. REFRDIR output consists of tabulated and plotted versions of the results of the computation. The tabulated output gives the horizontal phase velocities (apparent velocities) and intercept times for the forward and reverse profiles. For the plotted output, the apparent velocities and intercept times are used to define line segments, and forward and reverse time-distance plots are produced. PLOT2 (Appendix B) is used to produce the plots.

129. Example. Figures 61 and 62 illustrate the use of REFRDIR to solve a direct seismic refraction problem. The hypothetical model is shown in Figure 61, and the spread length was selected as 150 m. Computed time intercepts, see Figure 62, are indicated on the plot in Figure 61. This example is important because it illustrates that intuitive predictions of interface dip from apparent velocities or of apparent velocities from dip may be incorrect. For the example in Figures 61 and 62, intuition and experience might lead one to expect that the apparent velocity in the forward direction for interface 3 would be greater than V_3 ; however, the results from REFRDIR (see Figure 62) show that this is not the case.

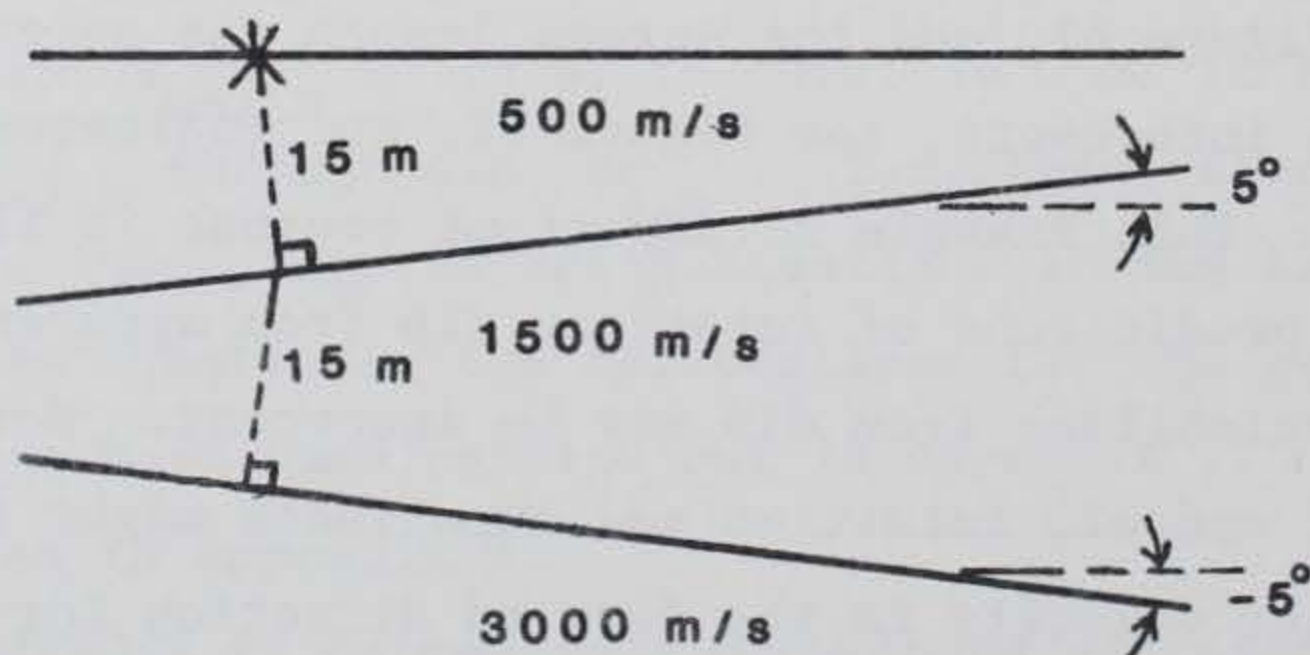
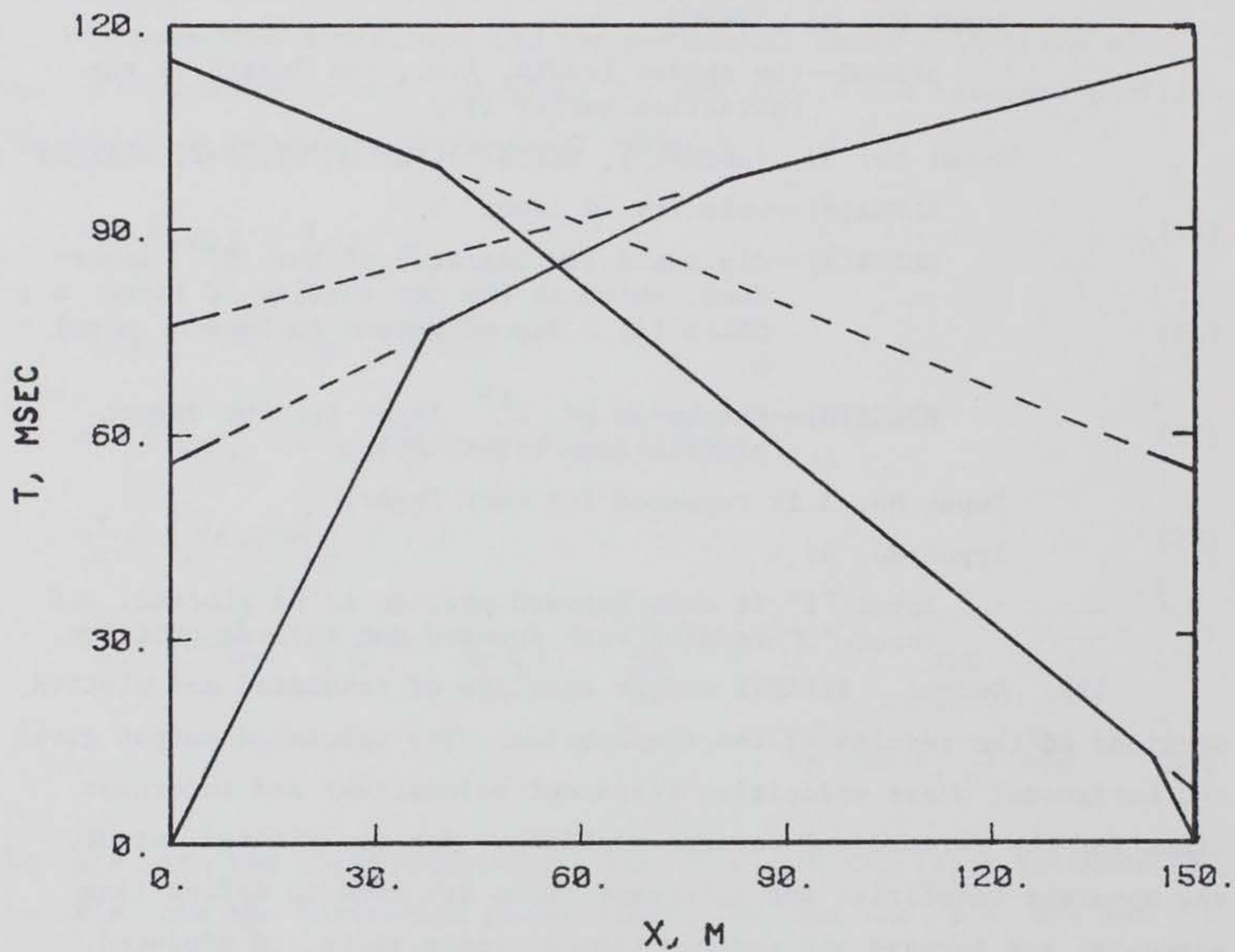


Figure 61. Three-layer model and first-arrival time-distance plot produced by REFRDIR

```

INPUT NUMBER OF LAYERS IN MODEL
=3
INPUT LENGTH OF SHOT SPREAD
=150
FOR EACH LAYER INPUT A LINE ENTRY WITH THE FOLLOWING DATA
SEPARATED BY COMMAS: LAYER VELOCITY, DIP OF INTERFACE,
LAYER THICKNESS

=500, 0, 15
=1500, 5, 15
=3000, -5,
VELOCITIES ARE IN METERS/SEC (OR FT/SEC), TIMES ARE IN
MILLISECS AND LAYER THICKNESSES ARE IN METERS. (FT)

THERE ARE 3 LAYERS IN THIS MODEL

LAYER NO.    VELOCITY    DIP (DEGREES)    H+    H-
1            500.        0.                15.0   2.0
2            1500.       5.0               15.0   40.9
3            3000.       -5.0

0

***** CALCULATED RESULTS *****

THE HORIZONTAL PHASE VELOCITIES AND THE INTERCEPT TIMES
FOR THE DIRECT (+) AND REVERSED (-) PROFILES.

INTERFACE NO.  PHASE VEL+    PHASE VEL-    T+    T-
2              2000.851     1207.041     56.6   7.5
3              3896.644     2497.997     76.4   55.1
INPUT 1 IF YOU WISH TO PLOT FORWARD
PROFILE LINE ONLY
ENTER 2 TO PLOT FORWARD AND REVERSEPROFILE
=2

```

Figure 62. Tabular output from REFRDIR for case shown in Figure 61

REFRINV

130. REFRINV uses the measured horizontal phase velocities (apparent velocities) and intercept times obtained from the direct and reversed profiles from refraction surveys to determine the velocities in the layers, the dip angles of the layer interfaces, and the layer "thicknesses." It is an inverse program, i.e., it gives, for its computed output, the parameters used as the input for the direct program, REFRDIR. On the other hand, the input of REFRINV corresponds to the output of REFRDIR.

131. This program uses the same equations that are used by REFRDIR. However, it uses them in opposite order to compute the physical properties of the medium by means of a "layer stripping" technique. That is, the program uses the measured data to find the properties of the first layer and then uses the measured data and the properties of the first layer to find the properties of the second layer and so on. REFRINV also uses the notation and the geometric parameters illustrated in Figure 60.

132. REFRINV has for its input: (a) the number of layers, (b) the velocity in the first layer, (c) the horizontal phase velocities and (d) the intercept times for the refracted waves from both the direct and reversed profiles. The program computes and prints out: (a) the velocity in each layer, (b) the layer "thicknesses," and (c) the dip of each interface (the first interface is the air/ground boundary and it is assumed to be horizontal). The phase velocities and layer velocities are given in metres/msec (ft/msec), the layer "thicknesses" are computed in metres (ft), and the dips in degrees. Like program REFRDIR, REFRINV assumes: (a) layer velocities increase monotonically with depth, (b) the velocity is constant in any given layer, and (c) interfaces are planar and have a common strike.

133. REFRINV makes use of the following equations (see Figure 60):

$$\theta_{i,n}^{\pm} \pm \psi_1 = \arcsin (\alpha_1 / V_n^{\pm}) \quad (20)$$

$$\theta_{m,n}^{\pm} + \psi_m = \arcsin \left[(\alpha_m / \alpha_{n-1}) \sin \frac{\pm}{m-1,n} \right] \quad (21)$$

$$\alpha_{n-1}/\alpha_n = \sin \theta_{n-1,n}; \theta_{n-1,n}^+ = \theta_{n-1,n}^- = \theta_{n-1,n} \quad (22)$$

$$H_{n-1}^+ = \frac{0.5\alpha_{n-1}}{\cos \theta_{n-1,n}} \quad T_{o,n}^{\pm} = \sum_{i=1}^{n-2} \frac{H_i^+}{\alpha_i} (\cos \theta_{i,n}^+ + \cos \theta_{i,n}^-) \quad (23)$$

$$\cos \theta_{n-1,n} = \frac{1 - (\alpha_{n-1}/\alpha_n)^2}{2} \quad (24)$$

where the α 's are the layer velocities, V 's are the phase velocities, the T 's are the intercept times, H 's are the layer "thicknesses," and the ψ 's are angles between interfaces.

134. Equations 20 through 24 are used iteratively: the input data for the second layer and the results from the first layer are used to find the results for the second layer; the input data for the third layer and results from the first and second layers are used to find the results for the third layer, and so on. This routine will become clearer after examination of Appendix J, where these equations are used in the general case of finding the velocities for four layers.

135. Input. The input to REFRINV is in free-field format and is summarized below:

Input No. 1: NLAYRS, V1

NLAYRS--number of layers (obtained as the number of straightline segments in the time-distance plot)

V1--true velocity of layer 1 (inverse slope of line segment passing through the origin of time-distance plot)

Input No. 2: (VPLUS(N), VMINUS(N), TPLUS(N), TMINUS(N), N=2, NLAYRS)

VPLUS(N), VMINUS(N)--forward and reverse apparent velocities respectively for the N^{th} interface

136. Output. The output of RESINV consists of two lists. The first list just summarizes the input data, while the second list presents

the calculated results: true layer velocities, interface dips, and layer thicknesses.

137. Example. Figure 63 is an example of the output of REFRINV. The input for this example is just the output from the REFRDIR example presented earlier in Figure 62. Note that the calculated results in Figure 63 agree with input model in Figure 62.

```

=3.5
=2.000851,1.207041,56.6,7.5
=3.386644,2.497997,76.4,55.1
  VELOCITIES ARE IN METERS/MILLISEC, TIMES ARE IN MILLISEC
  AND LAYER THICKNESSES IN METERS

  NO. OF REFRACTIONS = 2; FIRST-LAYER VELOCITY IS: 0.500

  INPUT DATA: PHASE VELOCITIES AND INTERCEPTS OF REFRACTIONS
  MEASURED ON DIRECT (+) AND REVERSED (-) PROFILES

  INTERFACE NO.  PHASE VEL+  PHASE VEL-  T+  T-
                2.001      1.207      56.6  7.5
                3.897      2.498      76.4  55.1

          ***** CALCULATED RESULTS *****
  THE WAVE VELOCITIES, INTERFACE DIPS AND LAYER THICKNESSES

  LAYER NO.  VELOCITY  DIP (DEG)  H+  H-
    1         0.500      0.         15.0  3.0
    2         1.500      5.0        14.9  40.9
    3         3.000     -5.0
  
```

Figure 63. Output from REFRINV using the calculated results in Figure 62 from REFRDIR as the input data

CROSSHOLE: Time-Sharing Version

138. The basic algorithms used by CROSSHOLE are documented in Butler, Skoglund, and Landers (1978); this basic documentation will not

be repeated here. Rather, the changes necessary to convert to remote-user or time-sharing operations are discussed and examples of the new input/output format are presented. The following four changes were made:

- a. Formatted input changed to allow free-field input.
- b. Input is from data files to avoid on-line input during program execution.
- c. Input sequence changed to eliminate redundant or duplicate input data.
- d. Considerable reformatting of program output to allow printing on 8.5-in.- (21.6-cm-) wide terminal paper.

CROSSHOLE is listed in Appendix K.

Input

139. All input is in free-field format and is from a data file (except Input No. 1 below). The input sequence and parameter descriptions are given below:

Input No. 1: DIN (1)

DIN (1)--name of input data file

Input No. 2: TITLE

TITLE--identification label for the crosshole data set

Input No. 3*: LIN, IOP1, N, IOP2, ISUM, M, DIST, AZIM,
VFIRST, VLAST, DLLAST, IMAX, DELGS, IPUN

LIN--line number followed by blank

IOP1--input option code

1 for arrival times

2 for apparent velocities

3 for true velocity profile and arrival times

4 for true velocity profile and apparent

5 for true velocity profile

N--storage key for output options, dimensions profiles
for summary tables

* The data file consists of line numbers followed by blanks, with data entries which follow on each line separated by blanks or commas as delimiters.

IOP2*output option code

- 0 Standard output, primarily for IOP1 = 1 or 2
- 1 For TABDUM, apparent velocity as a function of hole spacing
- 2 For SUMMARY table of three-hole set, P- and S-wave data
- 3 For SUMTWO comparison of computed apparent velocities with measured apparent velocities for known velocity profile
- 7 For carrying over the previous true velocity profile

ISUM--type of summary table. One for partial and two for full summary table

M--number of records per hold set

DIST--horizontal surface distance between boreholes

AZIM--hole pair azimuth, clockwise from north (in degrees)

VFIRST--first layer true velocity (if not defined by the data)

VLAST--deepest layer true velocity (if not defined by the data)

DLLAST--depth to deepest layer (if known)

IMAX--number of true velocity layers (for input options 3, 4, and 5)

DELGS--vertical geophone spacing (for input option 5 only)

IPUN--output punch option (for use with option 5)

Input No. 4: (LIN, SZ(J), SX(J), SY(J), GZ(J), GX(J), GY(J),
J = 1, M)

LIN--line number followed by blank

SZ(J)--source depth of Jth record

SX(J)--source local x-derivation, from borehole survey (north direction positive)

SY(J)--source local y-deviation, from borehole survey (east direction positive)

* Currently, only the IOP2 = 0 option has been formatted for output on 8.5-in.-wide terminal paper. For all other output options, the output should be directed to a batch printer or wide-paper terminal.

GZ(J),GX(J),GY(J)--geophone/receiver depth, x , and
y for Jth record

For IOP1 = 1 or 3

Input No. 5: (LIN, TR(J,N), J = 1,M)

LIN--line number followed by space

TR(J,N)--arrival time for Jth record

For IOP1 = 2 or 4

Input No. 5: (LIN, VA(J,N),J = 1,M)

LIN--line number

VA(J,N)--apparent velocity for Jth record

For IOP1 = 3, 4, or 5

Input No. 6: LIN, (DL(I,N) I = 1, IMAX-1)

LIN--line number

DL(IN)--thicknesses of specified true velocity layers

Input No. 7: LIN(VL(I,N), I = 1, IMAX-1)

LIN--line number

VL(I,N)--true velocities

Output

140. Three types of printed output are generated by CROSSHOLE:
(a) a summary tabulation of the input data; (b) a list of caution and
alternative interpretation messages; (c) a tabulation of the CROSSHOLE
interpretation or calculation results.

Examples

141. Figure 64 is an example of input data file for a case where
arrival times are input. Figure 65 is the output from CROSSHOLE for the
input data file in Figure 64. The caution messages in Figure 65 call
attention to the fact that many of the interface locations are poorly
defined due to an insufficient number of apparent velocity values in
each of the velocity zones or layers.

142. Typically all available information is utilized in develop-
ing representative velocity profiles for a site. Seismic refraction and
uphole/downhole seismic results, if available, are examined. Also, any
borehole log data are examined. Representative velocities which are

```

100          - S-WAVE - D/S TOE - P TO Q = 10 FT
110 1,.,.,9,10.2,130,.,.,.,.
120 5,-0.061,-0.093,5,-0.003,0.013
130 10 -0.055,-0.085,10,0.019,0.062
140 15 -0.160 -0.241 15 0.032 0.078
150 20 -0.078 -0.273 20 0.078 0.002
160 25 -0.110 -0.445 25 0.103 -0.047
170 30 -0.033 -0.530 30 0.192 -0.126
180 35 -0.060 -0.649 35 0.314 -0.165
190 40 -0.087 -0.729 40 0.424 -0.214
200 45 -0.102 -0.803 45 0.561 -0.230
210 14
220 13
230 15
240 18
250 15.5
260 15.5
270 14.5
280 16
290 16.5

```

Figure 64. Example of the format of an input data file for CROSSHOLE

finally accepted are "averaged" values of all values available. Interface depths are guided by borehole data if available.

ENTER THE NAME OF THE DATA FILE YOU WANT TO PROCESS
#SARPO

CROSSHOLE DATA - S-WAVE - D/S TOE - P TO Q = 10 FT

HORIZONTAL DISTANCE BETWEEN HOLES IS 10.2

DEPTH SHOT	DEPTH GEO	DIRECT DISTANCE	ARRIVAL TIME	APPARENT VELO	SHOT HOLE X-DEV	SHOT HOLE Y-DEV	GEO HOLE X-DEV	GEO HOLE Y-DEV
5.0	5.0	10.2	0.0140	732.	-0.06	-0.09	-0.00	0.01
10.0	10.0	10.3	0.0130	790.	-0.06	-0.08	0.02	0.06
15.0	15.0	10.3	0.0150	688.	-0.16	-0.24	0.03	0.08
20.0	20.0	10.3	0.0150	573.	-0.08	-0.27	0.08	0.00
25.0	25.0	10.4	0.0155	669.	-0.11	-0.45	0.10	-0.05
30.0	30.0	10.4	0.0155	669.	-0.03	-0.53	0.19	-0.13
35.0	35.0	10.3	0.0145	714.	-0.06	-0.65	0.31	-0.16
40.0	40.0	10.3	0.0160	643.	-0.09	-0.73	0.42	-0.21
45.0	45.0	10.3	0.0165	621.	-0.10	-0.80	0.56	-0.23

CROSSHOLE DIAGNOSTIC - S-WAVE - D/S TOE - P TO Q = 10 FT

EXECUTION CHECK - LAYER 1 - DEPTH 1 - DOWN 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 6.0
COULD BE ANYWHERE BETWEEN 5.0 AND 10.0

EXECUTION CHECK - LAYER 2 - DEPTH 2 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 13.6
COULD BE ANYWHERE BETWEEN 10.0 AND 13.6

EXECUTION CHECK - LAYER 3 - DEPTH 3 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 18.4
COULD BE ANYWHERE BETWEEN 15.0 AND 18.4

EXECUTION CHECK - LAYER 4 - DEPTH 4 - DOWN 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 21.4
COULD BE ANYWHERE BETWEEN 21.4 AND 25.0

EXECUTION CHECK - LAYER 5 - DEPTH 6 - DOWN 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 30.9
COULD BE ANYWHERE BETWEEN 30.9 AND 35.0

EXECUTION CHECK - LAYER 6 - DEPTH 7 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 38.8
COULD BE ANYWHERE BETWEEN 35.0 AND 38.8

EXECUTION CHECK - LAYER 7 - DEPTH 8 - UP 1
CAUTION - THE INTERFACE CALCULATED TO BE AT 44.3
COULD BE ANYWHERE BETWEEN 40.0 AND 44.3

CROSSHOLE INTERPRETATION - S-WAVE - D/S TOE - P TO Q = 10 FT

INTERFACE DEPTH			COMPUTED TRAVEL TIMES, SECONDS				APPARENT		
GEO DEPTH	SHOT DEPTH	TRUE VELOCITY	DIRECT	DOWN 1 LAYER	DOWN 2 LAYER	DOWN 3 LAYER	UP 1 LAYER	COMPUTED	MEASURED
5.0	5.0	761.	0.0135				0.0363	*****	
10.0	10.0	761.	0.0135				0.0293	*****	
< 13.6									
15.0	15.0	688.	0.0150		0.0232	0.0332	0.0152	688.	688.
< 18.4									
20.0	20.0	573.	0.0180	0.0180	0.0273		0.0180	573.	573.
< 21.4									
25.0	25.0	669.	0.0155	0.0207				669.	669.
30.0	30.0	669.	0.0155	0.0155				669.	669.
< 30.9									
35.0	35.0	714.	0.0145					714.	714.
< 38.8									
40.0	40.0	643.	0.0160				0.0160	643.	643.
< 44.3									
45.0	45.0	621.	0.0165				0.0165	621.	621.

MEAN DIFFERENCE = 0.03 ♦
STANDARD DEVIATION OF DIFFERENCE = 1.91 ♦

♦ PERCENT OF MEASURED VELOCITY

Figure 65. Output from CROSSHOLE for the input data file shown in Figure 64

PART V: SUMMARY AND FUTURE PLANS

Summary

143. This report presents the results of an effort directed to the improvement of geophysical data acquisition, processing, and interpretation. The major part of the work involves the adaptation of existing or development of new computer programs for processing and interpreting geophysical data. Some of the work can be described as new and, perhaps, innovative, while other parts of the work involve the implementation of existing or state-of-the-art techniques to Corps of Engineers geotechnical applications. The result is the compilation of a rather diverse group of computer programs and methodologies for the electrical resistivity, microgravimetric, and seismic methods.

144. Three computer programs for processing and interpreting electrical resistivity data are presented and documented. RESDIR and RESINV are programs for use with vertical resistivity sounding surveys. For a given model of subsurface resistivity variations, RESDIR computes the apparent resistivity as a function of electrode spacing for an expanding electrode array; this capability is useful for predicting the response or applicability of resistivity soundings to a suspected or postulated resistivity variation. RESINV attempts to determine a "best-fit" subsurface resistivity model directly from the field data; some expertise is required on the part of the interpreter in specifying an initial or "best-guess" model for input to the program. RESDAT is a general purpose resistivity data processing program. Both vertical sounding and horizontal profiling survey data can be handled by RESDAT; and for the case of vertical sounding data, an option is available for interpreting the processed data using a subroutine version of RESINV.

145. Three computer programs are documented for use in connection with microgravity surveys (actually the programs and techniques can be with gravity surveys on any scale). TIDES computes the theoretical earth-tide variation at any location and is used in conjunction with base station reoccupations to assure consistent gravimeter performance

during field surveys. The program TALGRAD computes gravity and gravity-gradient profiles across two-dimensional models. HILBERT computes the Hilbert transform of a discrete profile data set; if the profile data set is the horizontal gravity-gradient profile over a two-dimensional structure, then the Hilbert transform profile will be the vertical gravity gradient. In addition to the three computer programs, two microgravity survey methodologies are presented: (a) a technique for reduction of errors in microgravity surveying by the use of optimal gravity station occupation schemes; and (b) the use of polynomial surface fitting for determining the regional field component in a set of data.

146. Several computer programs for processing and interpreting seismic refraction and crosshole survey data are documented. Four programs are presented for digitizing, processing, and interpreting seismic refraction analog field data; use of these programs considerably expedites the processing of refraction data. Two programs are presented for interpretation of seismic refraction data, REFRDIR and REFRINV. The program REFRDIR computes first-arrival, time-distance data for a specified subsurface velocity model. REFRINV determines parameters of a subsurface velocity model, consisting of layer thicknesses and velocities, directly from processed field data. Finally, changes made to the program CROSSHOLE are documented. Specifically, CROSSHOLE can now be executed from time-sharing terminals.

147. Examples of the use of each of the computer programs are presented. Some of the examples are quite brief. Also, some of the examples appear in other reports in greater detail (see Preface and Part I for discussion of companion research efforts). However, some of the examples are presented in a detailed fashion and appear here for the first time.

Future Plans

148. Recommendations for future work to further automate geophysical data processing and interpretation in support of geotechnical

investigations are listed below:

- a. Obtain microcomputer for use in the field and convert RESDIR, RESINV, and RESDAT to execute on it; this will make available in the field rigorous resistivity sounding interpretations.
- b. Pursue the development of automated pole-dipole resistivity data processing and interpretation techniques.
- c. Acquire or develop a computer program for automatically computing terrain corrections to microgravity survey data.
- d. Develop a general purpose microgravity data-processing program for use with field microcomputers.
- e. Initiate field digital recording of seismic data to eliminate the necessity of "picking" field analog records.
- f. Initiate data-processing techniques on field micro-computer systems.
- g. Incorporate rigorous seismic interpretation procedures in conjunction with data-processing techniques.

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APPENDIX A: RESDIR LISTING

RESDIR

14:38:10 05/26/82

FILE PAGE NO. 1

```

10** HUN *,ROSD441/PLOTS,E;ROSD441/PLOTLL,E
20   INTEGER E
30   COMMON/Z1/E,M,N/Z2/DELX,SPAC
40   COMMON/ZA3/P(99)/ZA4/R(134)
50   DIMENSION FLTR1(29),FLTR2(34)
60   DIMENSION SN(30),R1(31),ASP(100)
70   DATA(FLTR1(I),I=1,29)/.00046256,=.0010907,.0017122,=.0020687,
80   &.0043048,=.0021236,.015995,.017065,.098105,.21918,.64722,1.1415,
90   &.47819,-3.515,2.7743,-1.201,.4544,=.19427,.097364,=.054099,.031729
100  &,.019109,.011656,=.0071544,.0044042,=.002715,.0016749,=.0010335,
110  &.00040124/
120  DATA(FLTR2(I),I=1,34)/.000238935,.00011557,.00017034,.00024955,
130  &.00036665,.00053753,.0007896,.0011584,.0017008,.0024959,.003064,
140  &.0053773,.007893,.011583,.016998,.024934,.036558,.053507,.070121,
150  &.11319,.16192,.22363,.28821,.30276,.15523,=.32026,=.53557,.51787,
160  &,.196,.054394,=.015747,.0053941,=.0021446,.000665125/
170C
180C INPUT NO. 1   ARRAY CHOICE, INPUT=
190C     1==FOR SCHLUMBERGER,
200C     &==FOR WENNER,
210C     3==FOR BIPOLE=BIPOLE,
220C INPUT NO. 2   SPAC,E,M           (FORMAT=FREE)
230C     SPAC = CLOSEST A OR S SPACING (REAL)
240C     E     = NUMBER OF MODEL LAYERS (INTEGER)
250C     M     = NUMBER OF FIELD READINGS (INTEGER) , 6/DECADE
260C INPUT NO. 2A  ENTER ONLY FOR BIPOLE=BIPOLE ARRAY, INPUT=
270C     1==IF N=VALUES ARE VARIED,
280C     0==IF A=SPACINGS ARE VARIED,
290C INPUT NO. 2B  ENTER ONLY FOR BIPOLE=BIPOLE, IF VALUE ENTERED IN 2A WAS=
300C     1==INPUT N=VALUES (TOTAL M) IN INCREASING ORDER (FORMAT=FREE)
310C     0==INPUT ONE N=VALUE. (N,NE,1)
320C INPUT NO. 3   ENTER LAYER PARAMETERS. (TOTAL 2E-1, FORMAT=FREE)
330C     ORDER== H(1),H(2),...,H(E-1),R(1),R(2),...,R(E)
340C * * * * *
350C REPEAT FOR ADDITIONAL MODELS,
360C
370   1 FORMAT(V)
375   PRINT,'INPUT NO. 1---INDEX (ARRAY TYPE)'
380 1000 READ 1, INDEX
400   IF(INDEX.EQ.0) STOP
410   PRINT, 'INPUT NO. 2---SPAC,E,M'
420   READ 1, SPAC,E,M
430   IF(INDEX=2) 40,40,5
440   5 READ 1,IX
450   IF(IX.EQ.1) GO TO 20
460   J=1
470   GO TO 35
480  20 J=M
490  35 READ 1, (SN(I),I=1,J)
500  40 N=2*E-1
510   SPAC=ALOG(SPAC)
520   PRINT, 'INPUT NO. 3, MODEL PARAMETERS, THICKNESSES(H) AND
530   & RESISTIVITIES(R)---H(1),H(2), . . . ,H(E-1),R(1), . . . ,R(E)'
540   READ 1,(P(I), I=1,N)
550   PRINT 42

```

```

560 42 FORMAT(// " APPARENT RESISTIVITY VALUES")
570 IF(INDEX=2)43,45,47
580 43 PRINT 44
590 44 FORMAT(// " SCHLUMBERGER ARRAY"//)
600 GO TO 50
610 45 PRINT 46
620 46 FORMAT(// " WENNER ARRAY"//)
630 GO TO 50
640 47 PRINT 48
650 48 FORMAT(// " BIPOLE=BIPOLE ARRAY"//)
660 50 DELX = ALOG(10,)/6,
670 IF(INDEX=2) 70,80,300
680 70 Y=SPAC=19,*DELX=0.13069
690 DO 75 I=1,M+28
700 CALL TRANSFM(Y,I)
710 75 Y=Y+DELX
720 CALL FILTER(FLTR1,29)
730 GO TO 120
740 80 S=ALOG(2,)
750 Y=SPAC=10.8792495*DELX
760 DO 110 I=1,M+33
770 CALL TRANSFM(Y,I)
780 A=R(I)
790 Y1=Y+S
800 CALL TRANSFM(Y1,I)
810 R(I)=2,*A=R(I)
820 110 Y=Y+DELX
830 GO TO 119
840 300 M1=1
850 IF(LX,NE.1) GO TO 111
860 M1=M
870 M=1
880 111 DO 117 I=1,M1
890 Y=SPAC=10.8792495*DELX
900 A=SN(I)
910 A1=ABS(A-1,)
920 S1=ALOG(A1)
930 IF(A,LT.1,) Y=Y+ALOG(A)
940 B=1.
950 IF(A,LT.1,) B=A*A+A-1.
960 S2=ALOG(A)
970 S3=ALOG(A+1,)
980 DO 116 J=1,M+33
990 Y1=Y+S1
1000 CALL TRANSFM(Y1,J)
1010 AA=R(J)/A1
1020 Y1=Y+S2
1030 CALL TRANSFM(Y1,J)
1040 AA=AA+2,*R(J)/A
1050 Y1=Y+S3
1060 CALL TRANSFM(Y1,J)
1070 R(J)=(AA+R(J)/(A+1,))*A*(A+1,)*A1/(2,*B)
1080 116 Y=Y+DELX
1090 IF(IX,NE.1) GO TO 117
1100 CALL FILTER(FLTR2,34)

```



```
1110      R1(I)=R(I)
1120 117  CONTINUE
1130      IF(M,NE,1) GO TO 119
1140      M=M1
1150      GO TO 120
1160 119  CALL FILTER(FLTR2,34)
1170 120  PRINT 125,E
1180 125  FORMAT(/I3," LAYER MODEL,")
1190      PRINT 130
1200 130  FORMAT(/5X,"LAYER NO.",3X,"THICKNESS",3X,"RESISTIVITY"/)
1210      DO 140 I=1,E=1
1220          J=I
1230      PRINT 135,J,P(I),P(I+E=1)
1240 135  FORMAT(9X,I2,5X,F8,3,7X,F8,3)
1250 140  CONTINUE
1260      PRINT 145,E,P(N)
1270 145  FORMAT(9X,I2,20X,F8,3)
1280      IF(INDEX=2) 205,205,150
1290 150  IF(IX,NE,1) GO TO 190
1300      SP=EXP(SPAC)
1310      PRINT 160,SP
1320 160  FORMAT(/" BIPOLE A=SPACING =",F6,2)
1330      PRINT 170
1340 170  FORMAT(/10X,"N",9X,"RHO"/)
1350      DO 185 I=1,M
1360      PRINT 180,SN(I),R1(I)
1370 180  FORMAT(7X,F7,2,3X,F9,3)
1380 185  CONTINUE
1390      GO TO 240
1400 190  PRINT 200,SN(1)
1410 200  FORMAT(/" BIPOLE N=SPACING =",F6,2)
1420 205  PRINT 210
1430 210  FORMAT(/7X,"SPACING",7X,"RHO"/)
1440      X=SPAC
1450      DO 230 I=1,M
1460          ASP(I)=EXP(X)
1470      PRINT 220, ASP(I),R(I)
1480 220  FORMAT(6X,F7,2,3X,F9,3)
1490 230  X=X+DELX
1500      PRINT, "DO YOU WANT DATA PLOTS YES(1), NO(2)"
1510      READ 1, II
1520      IF(II,EQ,2) GO TO 240
1530      PRINT, "LINEAR(1) OR LOG=LOG(2)"
1540      READ 1, JJ
1550      IF(JJ,EQ,2) GO TO 235
1560      CALL PLOT2(ASP,R,M)
1570      GO TO 240
1580 235  CALL PLOTLL(ASP,R,M)
1590 240  GO TO 1000
1600      END
1610      SUBROUTINE TRANSFM(Y,I)
1620      INTEGER E
1630      COMMON/Z1/E,M,N
1640      COMMON/ZA3/P(99)/ZA4/R(134)
1650      DIMENSION T(50)
```

```
1660      U=1./EXP(Y)
1670      T(1)=P(N)
1680      DO 30 J=2,E
1690          A=EXP(-2.*U*P(E+1-J))
1700          B=(1.-A)/(1.+A)
1710          RS=P(N+1-J)
1720          TPR=RS*B
1730          T(J)=(TPR+T(J-1))/(1.+TPR*T(J-1)/(RS*RS))
1740      30  CONTINUE
1750      R(I)=T(E)
1760      RETURN
1770      END
1780      SUBROUTINE FILTER(FLTR,K)
1790      INTEGER E
1800      COMMON/Z1/E,M,N
1810      COMMON/ZA4/R(134)
1820      DIMENSION RES(31),FLTR(K)
1830      DO 20 I=1,M
1840          RE=0
1850          DO 10 J=1,K
1860              B=FLTR(J)*R(I+K-J)
1870          10  RE=RE+B
1880          20  RES(I)=RE
1890          DO 30 I=1,M
1900          30  R(I)=RES(I)
1910      RETURN
1920      END
```

APPENDIX B: PLOT2 AND PLOTLL INPUT INSTRUCTIONS AND LISTINGS

Instructions for PLOT2

All input is in free-field format, and the program will call for the variables by name. The plot specification input variables are indicated in Figure B1.

Input No. 1: X \emptyset , Y \emptyset , SFX, SFY, IA, IDASH, THETA

X \emptyset , Y \emptyset --X and Y coordinates of the origin on the paper, in inches from the lower left of plotting surface

SFX, SFY--scale factors in the X and Y directions, respectively, in user units per inch of plot

IA--axes specification;

0--X and Y axes drawn

1--no axes drawn

2--X and Y axes drawn plus lines to form right and top border

IDASH--=0, plots solid line connecting data points, $\neq 0$, plots dashed line

THETA--angle in degrees between X-axis and long axis of plotter, counterclockwise positive

Input No. 2: HTX, XL, XS, NDX, N $_X$, SPX, ITX

HTX--height of characters in inches (0.1 is typical) for X-axis

XL--length of X-axis in inches

XS--starting point of X-axis from origin (X0) in inches

NDX--number of digits to right of decimal in axes labels

NPX--power of 10 by which the scale is to be multiplied

SPX, ITX--input 0 for both

Input No. 3: HTY, YL, YS, NDY, NPY, SPY, ITY

Exactly analogous to Input No. 2 except for Y-axis.

Input No. 4: X-LABEL

Input title of X-axis

Input No. 5: Y-LABEL

Title for Y-axis

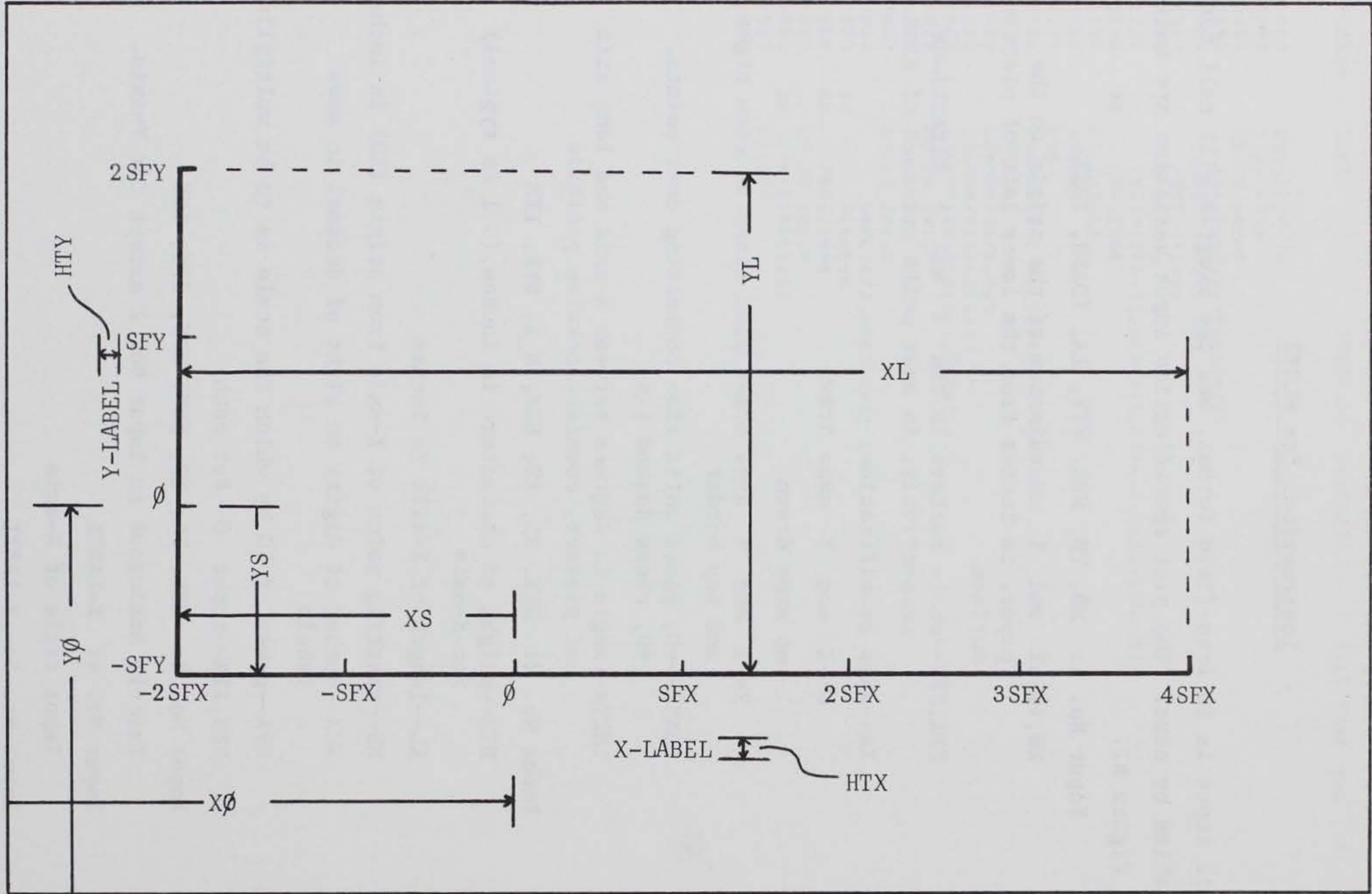


Figure B1. Definition of plot specification input parameters for PLOT2. X_0 , Y_0 , X_S , Y_S , X_L , and Y_L are in inches. SFX and SFY are in user units per inch.

Input No. 6: SL1, SL2, BL

Input only if IDASH \neq 0

SL1, SL2, BL--length of dashes and blank in inches
(two different dash lengths, if desired,
with constant blank length)

```

1000C ***** SUBROUTINE FOR TEKTRONIX 4062 DIGITAL PLOTTER *****
1010 SUBROUTINE PLOTS(IDT)
1020 CHARACTER *10 FMT/10M(156A1,14)/,IASC*4
1030 DIMENSION KP(156),IBCD(1),IASB(2),IOUT(32),ITAB(4,16)
1040 INTEGER HIY,HIYP,XLOY,XLOYP,HIX,HIXP
1050 LOGICAL L1,L3
1060 DATA C1,C2,C3 /0,46875,0,01464844,0,00366211/
1070 DATA IC1,IC2,IC3,IC4,IC5 /134217728,262144,512,128,4/
1080 DATA IESC,IE,IGS /3623878656,35328,3692314112/
1090 DATA KP(1),KP(3),IRPK /3623878656,5368709120,5502926848/
1100 CALL FPARAM(1,160)
1110 ID = IDT
1120 IF(ID=69) 2,2,1
1130 1 ID = ID/IC1
1140 2 KP1 = IESC+ID*IC2+IE+29
1150 KP2 = KP1+6644 ; KP3 = KP1+8675 ; KP4 = KP1+1507
1160 PRINT 120,KP1,KP2,KP4,160,KP3
1170 KP(2) = ID*IC1 ; KP(4) = IESC
1180 KP(5) = KP(2) ; KP(6) = 75*IC1
1190 IC1 = 108+ID ; IK = 7 ; IC = IC1+102+ID
1200 KP1 = KP1+483 ; KP2 = KP1+4096
1230 L2 = 1
1240 HXF = .61111111 ; HYF = 446.7273
1250 HIYP = 0 ; XLOYP = 0 ; HIXP = 0
1260 HIXP = 0 ; LOXP = 0 ; IPNP = 0
1270 HP = 0. ; ANGP = 0.
1272 IX0 = 0
1274 IY0 = 0
1280 RETURN
1380C ***** WHERE *****
1390C *****
1400 ENTRY WHERE(XAV,YAV,FACT)
1410 KP3 = IESC+ID*IC2+70*IC3 ; KP4 = IESC+ID*IC2+76*IC3
1420 KP5 = IESC+ID*IC2+75*IC3 ; KP6 = IESC+ID*IC2+69*IC3
1430 PRINT 120,KP3
1440 PRINT,"WHEN PROMPT LIGHT COMES ON POSITION PEN,"
1450 8" PRESS CALL BUTTON AND RELEASE"
1460 PRINT 120,KP6
1470 PRINT 120,KP5
1480 READ FMT,IN1,IN2,IN3,IN4,IN5,IN6,IN7
1490 PRINT 120,KP4
1500 IN1 = IN1/IC1=32 ; IN2 = IN2/IC1=32
1510 IN3 = IN3/IC1=32 ; IN4 = IN4/IC1=32
1520 IN5 = (IN5/IC1=32)/8 ; IN6 = (IN6/IC1=32)/8
1530 XAV = IN1*C1+IN3*C2+IN5*C3 ; YAV = IN2*C1+IN4*C2+IN6*C3
1540 RETURN
1550C ***** PLOT *****
1560C *****
1570 ENTRY PLOT(X,Y,IPN)
1580 IPNX = IPN
1590 IX = X*273+IX0
1592 IY = Y*273+IY0
1600 IF(IPNX) 10,99,20
1610 10 IPNX = -IPNX
1620 IX0 = X*273

```

```
1622      IY0 = Y*273
1624      IX = IX0
1626      IY = IY0
1630      20 IF(IPNX=3) 40,30,90
1640      30 IF(KP(IK=1),EQ,IGS) GO TO 40
1642      KP(IK) = IGS
1650      IC = IC+29 ; IK = IK+1
1670      40 IF(IX.LT,0,OR,IY.LT,0,OR,IX.GT,4095,OR,IY.GT,2730) GO TO 95
1680      MIX = IX/IC4
1690      IX = IX-MIX*IC4
1700      MIX = MIX+32
1702      LOX = IX/IC5
1710      IXLO = IX-LOX*IC5
1720      LOX = LOX+64
1730      MIY = IY/IC4
1740      IY = IY-MIY*IC4
1750      MIY = MIY+32
1752      LOY = IY/IC5
1760      XLOY = 4*(IY-LOY*IC5)+IXLO+96
1770      LOY = LOY+96
1790      L1 = .F. ; L3 = .F.
1800      IF(IPNP.NE,IPN) L3 = .T.
1810      IPNP = IPN ; IS = 2
1820      IF(IK=147) 50,50,85
1830      50 IF(MIY=MIYP) 51,52,51
1840      51 KP(IK) = MIY*IC1
1850      IC = IC+MIY
1860      IK = IK+1
1870      MIYP = MIY
1880      L3 = .T.
1890      52 IF(XLOY=XLOYP) 54,58,54
1900      54 KP(IK) = XLOY*IC1
1910      IC = IC+XLOY
1920      IK = IK+1
1930      XLOYP = XLOY
1940      KP(IK) = LOY*IC1
1950      IC = IC+LOY
1960      IK = IK+1
1970      LOYP = LOY
1980      L1 = .T. ; L3 = .T.
1990      58 IF(LOY=LOYP) 60,62,60
2000      60 KP(IK) = LOY*IC1
2010      IC = IC+LOY
2020      IK = IK+1
2030      LOYP = LOY
2040      L1 = .T. ; L3 = .T.
2050      62 IF(MIX=MIXP) 64,70,64
2060      64 IF(L1) GO TO 66
2070      KP(IK) = LOY*IC1
2080      IC = IC+LOY
2090      IK = IK+1
2100      L3 = .T.
2110      66 KP(IK) = MIX*IC1
2120      IC = IC+MIX
2130      IK = IK+1
```

```

2140      MIXP = MIX
2150 70 IF(L3) GO TO 71
2160      IF(LOX=LOXP) 71,72,71
2170 71 KP(IK) = LOX*IC1
2180      IC = IC+LOX
2190      IK = IK+1
2200      LOXP = LOX
2210 72 GO TO (99,210,360) ,L2
2230 85 IC = MOD(IC,4095)
2240      IF(IC,EQ,0) IC = 4095
2250      ICL = ALOG10(IC)
2260      ICC = 0
2270      KP(IK) = IESC
2280      KP(IK+1) = KP(2)
2290      KP(IK+2) = IRPR
2300      IK = IK+2
2310      ENCODE (FMT,100) IK,ICL+1
2320 88 PRINT FMT,(KP(I),I=1,IK),IC
2330      READ FMT,ICK
2340      IF(ICK/IC1,EQ,73) GO TO 97
2350      IC = IC1
2360      IK = 4
2370      GO TO (50,93,72,220,270,91) ,IS=1
2380 90 IS = 7
2385      IF(IPNX,EQ,4) GO TO 92
2390      IF(IK=146) 91,91,85
2400 91 KP(IK) = IGS
2410      KP(IK+1) = 53*IC1
2420      KP(IK+2) = 107*IC1
2430      KP(IK+3) = 106*IC1
2440      KP(IK+4) = 63*IC1
2450      KP(IK+5) = 95*IC1
2460      IK = IK+6 ; IC = IC+453
2470 92 IS = 3
2480      GO TO 85
2490 93 PRINT 120,KP2,KP1
2500      RETURN
2510 95 IF(KP(IK=1),EQ,IGS) GO TO 72
2520      KP(IK) = IGS
2530      IK = IK+1 ; IC = IC+29
2540      IS = 4
2550      IF(IK=152) 72,72,85
2560 97 ICC = ICC+1
2570      IF(ICC=5) 88,98,98
2580 98 PRINT 120,KP2,KP1
2590      PRINT," PLOTTER OR PROGRAM ERROR"
2600      STOP "ERROR"
2610 99 RETURN
2620 100 FORMAT(T2,I3,T9,I1)
2630 120 FORMAT(2A4,A3,I3,A3)
2650C      ***** SYMBOL *****
2660C      *****
2670      ENTRY SYMBOL(X,Y,H,I,BCD,ANG,NC)
2680      IF(NC) 320,200,200
2690 200 IF(X=999,) 205,240,205
    
```



```
2700 205 IX = X*273+IX0
2710      IY = Y*273+IY0
2720      L2 = 2
2730      GO TO 30
2740 210 L2 = 1
2750      IS = 5
2760      IF (IK=123) 220,220,85
2770 220 IF (H=HP) 222,230,222
2780 222 CONTINUE
2790      HP = H
2800      KP(IK) = IESC
2810      KP(IK+1) = KP(2)
2820      KP(IK+2) = 73*IC1
2830      IC = IC+ID+144
2840      IK = IK+3
2850      YVAL = H*HYF
2860      XVAL = YVAL*HXF
2870      ENCODE(IASC,130) IFIX(XVAL+.5)
2875 130 FORMAT(I4)
2880      IST = 1
2890 224 L = 0
2900      DO 226 1 = 1,4
2910      IAC = FLD(L,9,IASC)
2920      IF (IAC,LT,48) GO TO 226
2930      KP(IK) = IAC*IC1
2940      IK = IK+1
2950      IC = IC+IAC
2960 226 L = L+9
2970      IF (IST) 228,230,240
2980 228 IST = 0
2990      KP(IK) = 44*IC1
3000      IK = IK+1
3010      ENCODE(IASC,130) IFIX(YVAL+.5)
3020      GO TO 224
3030 230 IF (ANG=ANGP) 232,240,232
3040 232 ANGP = ANG
3050      IST = 1
3060      KP(IK) = IESC
3070      KP(IK+1) = KP(2)
3080      KP(IK+2) = 74*IC1
3090      IK = IK+3
3100      IC = IC+ID+101
3110      ENCODE(IASC,130) IFIX(ANG+.5)
3120      GO TO 224
3130 240 CONTINUE
3140      KP(IK) = 4160749568
3150      IK = IK+1
3160      IC = IC+31
3170      IF (NC) 260,250,260
3180 250 CONTINUE
3182      CALL BCDASC(IHCD,IASB,6)
3190      IAC = FLD(9,9,IASB(2))
3192      KP(IK) = IAC*IC1
3200      IC = IC+IAC
3210      IK = IK+1
```

```

3220      GO TO 290
3230 260  CONTINUE
3240      NT = NC/4
3250      NL = NC-NT*4
3260      IF(NL.GT.0) NT = NT+1
3270      IF(NL.LE.0) NL = 4
3280      IAC = FLD(0,9,IBCD(1))
3290      IF(IAC.GT.127) GO TO 300
3300      IS = 0
3310      DO 270 M = 1,NT
3320      L = 0
3330      IF(M.LT.NT) JT = 4
3340      IF(M.GE.NT) JT = NL
3350      DO 270 J = 1,JT
3360      IAC = FLD(L,9,IBCD(M))
3370      KP(IK) = IAC*IC1
3380      IK = IK+1
3390      IC = IC+IAC
3400      IF(IK=151) 270,270,85
3410 270  L = L+9
3420 290  KP(IK) = IGS
3430      IK = IK+1
3440      IC = IC+29
3450      RETURN
3460 300  IF(NC.GT.7) GO TO 290
3470      CALL BCDASC(IBCD,IASB,NC)
3480      DO 310 M = 1,NT
3490      L = 0
3500      IF(M.LT.NT) JT = 4
3510      IF(M.GE.NT) JT = NL
3520      DO 310 J = 1,JT
3530      IAC = FLD(L,9,IASB(M))
3540      KP(IK) = IAC*IC1
3550      IK = IK+1
3560      IC = IC+IAC
3570 310  L = L+9
3580      GO TO 290
4000C      ***** SPECIAL SYMBOLS *****
4010C      *****
4020 320  CONTINUE
4030      DATA ITAB /
4040C      PLOT SYMBOLS
4050C      0 1
4060      & 133266,4860164,0,0,6428818,3158086,4860124,6,
4070C      2 3
4080      & 1050770,25762,0,0,4225170,4727252,0,0,
4090C      4 5
4100      & 1079570,4719072,0,0,592018,1648788,0,0,
4110C      6 7
4120      & 5310610,4727266,6,0,1181970,1646599,0,0,
4130C      8 9
4140      & 8358702,1851426,25745,0,555262,4850130,6,0,
4150C      10 11
4160      & 6666514,38496,2900661,1648923,8357742,4276676,1982471,25720,
4170C      12 13

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4180      & 149522,25732,0,0,555154,402,0,0,
4182C      14 (GAMMA)
4184      & 4599036,5025929,1805410,0,
4186C      15 SIGMA
4188      & 8592565,4989008,435,0/
4190      DATA INEG /=8388608/
4200      RAD = ANG*,01745329
4210      CTH = COS(RAD)
4220      STH = SIN(RAD)
4230      L2 = 3
4240      FM = 68,25*H
4250      XI = X*273+IX0
4260      YI = Y*273+IY0
4270      IP = 3
4280      IF(NC.LT.,=1) IP = 2
4282      IF(IP.EQ.,3) IPNP = -IPNP
4290      MC = IBCD(1)+1
4300      IF(MC.LT.,1.OR.,MC.GT.,16) GO TO 390
4302      IF(MC.GT.,14) FM = 39*H
4304      ISP = 2
4306      IF(MC.GT.,14) ISP = 0
4310      DO 350 IA = 1,4
4320      IT = ITAB(IA,MC)
4330      IF = 0
4340      IF(IT) 330,340,340
4350 330 IT = IT*INEG
4360      IF = 1
4370 340 DO 350 IB = 1,8
4380      IO = (IA-1)*8+IB
4390      IOUT(IO) = IT*IT/8*8
4400      IT = IT/8
4410      IF(IB.EQ.,8.AND.,IF.EQ.,1) IOUT(IO) = IOUT(IO)+4
4420 350 CONTINUE
4430      K = 1
4432 370 CONTINUE
4440      IF(IOUT(K)=7) 354,352,354
4450 352 IP = 3
4460      GO TO 380
4470 354 IF(IOUT(K)=6) 356,390,356
4480 356 OX = (IOUT(K)-ISP)
4490      OY = (IOUT(K+1)-ISP)
4500      IX = (OX*CTH+OY*STH)*FM+XI
4510      IY = (OX*STH+OY*CTH)*FM+YI
4520      GO TO (40,40,30) ,IP
4530 360 IP = 2
4540 380 K = K+2
4545      IF(K=31) 370,370,390
4550 390 L2 = 1
4560      GO TO 290
4570      END
4600C

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```

4610C      ***** NUMBER *****
4620C      *****
4630      SUBROUTINE NUMBER(X,Y,H,FPN,ANG,ND)
4640      CHARACTER FMTN *7,IBCN *50

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4650      FPNX = FPN
4660      NDI = 1
4670      IF (FPNX) 10,30,20
4680      10 FPNX = -FPNX
4690      NDI = 2
4700      20 IF (FPNX,LT,10) GO TO 30
4710      NDI = NDI + IFIX(ALOG10(FPNX))
4720      30 IF (ND) 50,40,40
4730      40 NDT = NDI+ND+1
4740      ENCODE (FMTN,110) NDT,ND
4750      ENCODE (IBCN,FMTN) FPN
4760      NC = NDT
4770      GO TO 80
4780      50 FPNX = FPN
4790      NDX = ND+1
4800      IF (NDX) 60,70,70
4810      60 FPNX = FPNX*10,**NDX
4820      NDI = MAX(NDI+NDX,1)
4830      70 ENCODE (FMTN,120) NDI
4840      ENCODE (IBCN,FMTN) IFIX(SIGN(ABS(FPNX)+.5,FPNX))
4850      NC = NDI
4860      80 CALL SYMBOL(X,Y,H,IBCN,ANG,NC)
4870      RETURN
4880      110 FORMAT(2H(F,I2,1H,,I1,1H))
4890      120 FORMAT(2H(I,I2,1H))
4900      END
5000C

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```

5010***** PLUT2 *****
5020      SUBROUTINE PLOT2(X,Y,N)
5030      DIMENSION X(1),Y(1)
5040      CHARACTER *70 LBX,LBY,LBX2,LBY2,LABT*1(70),
5050      &          FMT*6/6H(70A1)/,FIN*3/3H(V)/
5060      LOGICAL L1/,T,/
5070      DATA IN /5/
5080      IF (L1) PRINT,"READ X0,Y0,SFX,SPY,IA,LDASH,THETA"
5090      READ(IN,FIN) X0,Y0,SFX,SPY,IA,LDASH,THETA
5100      IF (SFX) ,99,
5105      SPX = 1. ; SPY = 1.
5110      IF (IA,EQ,1) GO TO 29
5120      LX = =1 ; LY = 1 ; LX2 = 1 ; LY2 = =1
5130      XL2 = 0. ; YL2 = 0. ; ITX = 1 ; ITY = 1
5140      IF (L1) PRINT,"READ HTX,XL,XS,NDX,NPX,SPX,ITX"
5150      READ(IN,FIN) HTX,XL,XS,NDX,NPX,SPX,ITX
5160      IF (L1) PRINT,"READ HTY,YL,YS,NDY,NPY,SPY,ITY"
5170      READ(IN,FIN) HTY,YL,YS,NDY,NPY,SPY,ITY
5180      IF (SPX,LE,0.) SPX = 1. ; IF (SPY,LE,0.) SPY = 1.
5190      IF (ITX,EQ,0) ITX = 1 ; IF (ITY,EQ,0) ITY = 1
5200      IF (HTX,LE,0.) GO TO 7
5210      IK = 1
5220      IF (L1) PRINT,"READ X=LABEL"
5230      1 READ(IN,FMT) LABT
5240      DO 2 I=1,70
5250      K = 71-I
5260      IF (LABT(K),NE,1H ) GO TO 3
5270      2 CONTINUE

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5280 3 GO TO (6,8,26,28) ,IK
5290 6 ENCODE(LBX,FMT) (LABT(I),I=1,K)
5300 LX = K
5310 7 IF(HTY.LE.0.) GO TO 9
5320 IK = 2
5330 IF(L1) PRINT,"READ Y=LABEL"
5340 GO TO 1
5350 8 ENCODE(LBY,FMT) (LABT(I),I=1,K)
5360 LY = K
5370 9 IF(IA.NE.2) GO TO 29
5380 IF(L1) PRINT,"READ HTX2,XL2,XS2,NDX2,NPX2,XY0"
5390 READ(IN,FIN) HTX2,XL2,XS2,NDX2,NPX2,XY0
5400 IF(L1) PRINT,"READ HTY2,YL2,YS2,NDY2,NPY2,YX0"
5410 READ(IN,FIN) HTY2,YL2,YS2,NDY2,NPY2,YX0
5420 IF(HTX2.LE.0.) GO TO 27
5430 IK = 3
5440 IF(L1) PRINT,"READ X=LABEL2"
5450 GO TO 1
5460 26 ENCODE(LBX2,FMT) (LABT(I),I=1,K)
5470 LX2 = K
5480 27 IF(HTY2.LE.0.) GO TO 29
5490 IK = 4
5500 IF(L1) PRINT,"READ Y=LABEL2"
5510 GO TO 1
5520 28 ENCODE(LBY2,FMT) (LABT(I),I=1,K)
5530 LY2 = K
5540 29 IF(IDASH.NE.0) GO TO 12
5550 TH = THETA*.0174532925
5560 S = SIN(TH) ; C = COS(TH)
5570 XCF = SPX*C/SFX ; XSF = SPX*S/SFX
5580 YSF = SPY*S/SFY ; YCF = SPY*C/SFY
5590 CALL PLOTS("A")
5600 CALL PLOT(X0,Y0,=5)
5610 DO 10 I = 1,N
5620 H = X(I)*XCF - Y(I)*YSF
5630 V = X(I)*XSF + Y(I)*YCF
5640 IF(I.EQ.1) CALL PLOT(H,V,3)
5650 10 CALL PLOT(H,V,2)
5660 GO TO 14
5670 12 IF(L1) PRINT,"DASHED LINE = SL1,SL2 = SOLID LENGTHS,"
5680 & " BL = BLANK LENGTH (INCHES)"
5690 IF(L1) PRINT,"READ SL1,SL2,BL"
5700 READ(IN,FIN) SL1,SL2,BL
5710 CALL PLOTS("A")
5720 CALL PLOT(X0,Y0,=3)
5730 CALL DASHED(X,Y,N,SFX/SPX,SFY/SPY,SL1,SL2,BL,THETA)
5740 14 IF(IA=1) ,98,
5750 XS = XS*SPX ; YS = YS*SPY
5760 IF(XL.LE.0.) GO TO 16
5770 XL = XL*SPX ; XST = XS*SFX/SPX
5780 CALL AXIS14(XS,YS,LBX,LX,HTX,XL,NDX,0,XST,SFX,SPX,
5790 & ITX,NPX,THETA)
5800 16 IF(YL.LE.0.) GO TO 17
5810 YL = YL*SPY ; YST = YS*SFY/SPY
5820 CALL AXIS14(XS,YS,LBY,LY,HTY,YL,NDY,1,YST,SFY,SPY,

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5830      &          ITY,NPY,THETA)
5840  17 IF(XL2,LE,0,) GO TO 18
5850      XL2 = XL2*SPX ; XS2 = XS2*SPX ; XY0 = XY0*SPY
5860      XST2 = XS2*SFX/SPX
5870      CALL AXIS14(XS2,XY0,LBX2,LX2,HTX2,XL2,NOX2,0,XST2,SFX,SPX,
5880      &          ITX,NPX2,THETA)
5890  18 IF(YL2,LE,0,) GO TO 98
5900      YL2 = YL2*SPY ; YS2 = YS2*SPY ; YX0 = YX0*SPX
5910      YST2 = YS2*SFY/SPY
5920      CALL AXIS14(YX0,YS2,LBY2,LY2,HTY2,YL2,NOY2,1,YST2,SFY,SPY,
5930      &          ITY,NPY2,THETA)
5940  98 CALL PLOT(0,,0,,999)
5950  99 RETURN
5960      ENTRY INFIL(INF)
5970      IN = INF ; L1 = ,F,
5980      RETURN
5990      END
6000C

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```

6010C      REM ***** "INITIATE DATA PLOT" SUBROUTINE *****
6020      SUBROUTINE DASHED(XB,YB,M,SFX,SFY,SL1,SL2,BL,THETA)
6030      DIMENSION XB(1),YB(1)
6040      INTEGER F,F2,D3
6050      REAL N1(2),N2,N5,N6,L1,L2
6060      LOGICAL L3
6070      COMMON /BASIC/ F,F2,H0,H5,L1,L2,N1,N2,N6,G0,G1,
6080      &          H0,R1,S3,S4,U1,U2,V0,V5,J0,D3,L3
6090      TH = THETA*,0174532925
6100      S = SIN(TH) ; C = COS(TH)
6110      XCF = C/SFX ; XSF = S/SFX
6120      YSF = S/SFY ; YCF = C/SFY
6130      N1(1) = SL1
6140      N1(2) = SL2
6150      N2 = BL
6160      F=1
6170      F2=0
6180      L3 = ,F,
6190      J0 = 2
6200      D3 = =1
6210      Q1 = XB(1)*XCF - YB(1)*YSF
6220      R1 = XB(1)*XSF + YB(1)*YCF
6230      CALL PLOT(Q1,R1,3)
6240      DO 100 I=2,M
6250      Q0 = Q1
6260      H5 = Q0
6270      R0 = R1
6280      V5 = R0
6290      Q1 = XB(I)*XCF - YB(I)*YSF
6300      R1 = XB(I)*XSF + YB(I)*YCF
6310      D1=(Q1-Q0)
6320      D2=(R1-R0)
6330      D0=SQRT(D1**2+D2**2)
6340      IF(D0) ,100,
6350      U1=D1/D0
6360      U2=D2/D0
6370      IF(F2,EQ,0) GO TO 10

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```

6380      L1=U1*N6
6390      L2=U2*N6
6400      M0=M5
6410      V0=V5
6420      CALL ENTRY1
6430      IF(F2.EQ.1) GO TO 100
6440      10 CALL SUBLIN
6450      IF(F2.NE.1) GO TO 10
6460      100 CONTINUE
6470      RETURN
6480      END
6490C

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6500C      REM ***** "PLOT DASHED=LINE" SUBROUTINE *****
6510      SUBROUTINE SUBLIN
6520      INTEGER F,F2,D3
6530      REAL N1(2),N2,N5,No,L1,L2
6540      LOGICAL L3
6550      COMMON /BASIC/ F,F2,M0,M5,L1,L2,N1,N2,No,U0,U1,
6560      6      R0,R1,S3,S4,U1,U2,V0,V5,J0,D3,L3
6570      M0=M5
6580      V0=V5
6590      IF(F.EQ.2) GO TO 20
6600      J0 = J0+D3
6610      L1=U1*N1(J0)
6620      L2=U2*N1(J0)
6630      D3 = -D3
6640      GO TO 30
6650      20 L1=U1*N2
6660      L2=U2*N2
6670      ENTRY ENTRY1
6680      30 M5=M5+L1
6690      V5=V5+L2
6700      IF(ABS(M5=Q0).GT.ABS(U1=Q0)) GO TO 70
6710      IF(ABS(V5=R0).GT.ABS(R1=R0)) GO TO 70
6720      F2=0
6730      IF(F.EQ.1) GO TO 50
6740      F=1
6750      40 M5L = M5
6760      V5L = V5
6770      L3 = .T.
6780      RETURN
6790      50 F=2
6800      60 IF(.NOT.L3) GO TO 65
6810      CALL PLOT(M5L,V5L,3)
6820      L3 = .F.
6830      65 CALL PLOT(M5,V5,2)
6840      RETURN
6850      70 M5=U1
6860      V5=R1
6870      L1=M5-M0
6880      L2=V5-V0
6890      N5=SQRT(L1**2+L2**2)
6900      IF(F2.EQ.0) GO TO 80
6910      No=N6=N5
6920      GO TO 110

```

```

6930 80 IF(F,EQ,2) GO TO 100
6940      N6=N1(J0)=N5
6950      GO TO 110
6960 100 N6=N2=N5
6970 110 F2=1
6980      IF(F=1) 60,60,40
6990      END
7000C

```

```

7010      SUBROUTINE AXIS14(X, Y, IBCD, NC, H, SIZE, NN, IXY, XMIN, DX,
7020      *SPACE, ITIC, NP10, THETA )
7030      DIMENSION LBL(2),IBCD(1)
7040      DATA IBCD1/4H      /,LBL/4H(X10,4H  ) /
7050      XY = IXY
7060      ANGLE = XY*90.+THETA
7070      TH = THETA*.01745329
7080      S = SIN(TH)
7090      C = COS(TH)
7100      TIC = SIGN(1,ITIC)
7110      SPAC = SPACE
7120      G = H
7130      P10 = NP10
7140      X2 = X
7150      Y2 = Y
7160      XT = 0.
7170      YT = 0.
7180      LINE = 2
7190      SIZ = SIZE
7200      IF ( SIZ) 1,16,100
7210 1 LINE = 3
7220      SIZ = =SIZ
7230 100 ND = NN
7240      NA = NN
7250      IF (ND) 3,2,2
7260 2 NDIG = ND + 1
7270      GO TO 30
7280 3 ND = 0
7290      NDIG = 0
7300 30 NSPACE = SIZ / SPAC + .5
7310      FNSPAC = NSPACE
7320      TL = FNSPAC * SPAC
7330      H02 = G * .5
7340      H07 = H02 / 3.5
7350      H07T24 = 4. * G
7360      POWER = 10. ** (=NP10)
7370      DELX = POWER * DX
7380      XMEN = POWER * XMIN
7390      ANG = 1. * XY
7400      NB = NC
7410      ALAB = 1.
7412      XYL = .18
7420      IF (NB) 5, 6, 6
7430 5 NB = =NB
7440      ALAB = =1.
7442      XYL = XYL+G
7450 6 TICXY = (2.*XY=1.)*ALAB*TIC*.1

```



```

7460 XTIC = TICXY * XY
7470 YTIC = TICXY * ANG
7480 AK = NB
7490 IF ( P10) 60,65,60
7500 60 AK = AK + 8.
7510 65 STITLE = 1L * .5 = (7.*AK = 3.) * H07 * .5
7520 TICM1 = .16 = TIC * .05
7530 ANOMIN = 24.
7540 XNUMB = XMEN
7550 LIN = 3
7560 NMAX = 0
7570 J = 0
7580 DO 12 I=J,NSPACE
7590 NDIGIT = NDIG
7600 CALL PLOT (X2, Y2, LIN )
7610 LIN = LINE
7620 X1 = XT+XTIC
7630 Y1 = YT+YTIC
7640 XP = X1*C = Y1*S + X
7650 YP = X1*S + Y1*C + Y
7660 CALL PLOT (XP, YP, 2 )
7670 IF (G) 7, 11, 7
7680 7 IF(MOD(I,ITIC)) 8,8,20
7690 8 ITEMP = .434294482 *ALOG(ABS(XNUMB)+.5 * 10.**(-ND))+1,
7700 IF(ITEMP)70,70,71
7710 70 ITEMP = 1
7720 71 NDIGIT = NDIGIT+ITEMP
7730 IF(XNUMB)9,10,10
7740 9 NDIGIT = NDIGIT + 1
7750 10 IF(NDIGIT = NMAX)77,77,76
7760 76 NMAX = NDIGIT
7770 77 FDIGIT = NDIGIT
7780 CENTER = (7. * FDIGIT = 3.) * H07 * .5
7790 XAND = ALAB * XY * ( TICM1 + CENTER ) = CENTER
7800 YAND = ALAB * ANG * ( TICM1 + H02) = H02
7810 X1 = XAND + XT
7820 Y1 = YAND + YT
7830 XP = X1*C = Y1*S + X
7840 YP = X1*S + Y1*C + Y
7850 CALL NUMBER (XP, YP, G , XNUMB, THETA, NA )
7860 20 XNUMB = XNUMB + DELX
7870 IF(ANOMIN=XAND)11,11,76
7880 78 ANOMIN = XAND
7890 11 CALL PLOT(X2, Y2, 3 )
7900 XT = XT + SPAC * ANG
7910 YT = YT + SPAC * XY
7920 X2 = XT*C = YT*S + X
7930 Y2 = XT*S + YT*C + Y
7940 12 CONTINUE
7950 IF (G) 13, 16, 13
7960 13 NX = NB/4
7970 IF(AMOD(NB,4))18,18,17
7980 17 NX = NX + 1
7990 18 DO 15 I=1,NX
8000 IF(IBCD(I)=IBCD1)19,15,19

```

```
8010 15 CONTINUE
8020 GO TO 16
8030 19 FNMAX = NMAX
8040 ANCID = (7. * FNMAX = 3.) * H07 * .5
8050 XTITLE = XY * (ANOMIN + ANOWID - ALAB * (ANOWID + XYL)) +
8060 .6 ANG * STITLE
8070 YTITLE = ANG * (YANO + ALAB * (G + .18)) + XY * STITLE
8080 XP = XTITLE*C = YTITLE*S + X
8090 YP = XTITLE*S + YTITLE*C + Y
8100 CALL SYMBOL(XP, YP, G, IBCD, ANGLE, NB )
8110 IF (P10) 14, 16, 14
8120 14 FNB = NB
8130 BN = (FNB + 1.) * G
8140 XTITLE = XTITLE + ANG * BN
8150 YTITLE = YTITLE + XY * BN
8160 XP = XTITLE*C = YTITLE*S + X
8170 YP = XTITLE*S + YTITLE*C + Y
8180 CALL SYMBOL (XP, YP, G, LBL, ANGLE, 7)
8190 XTITLE = XTITLE + ANG * H07T24 = XY*H02
8200 YTITLE = YTITLE + XY * H07T24 + ANG*H02
8210 XP = XTITLE*C = YTITLE*S + X
8220 YP = XTITLE*S + YTITLE*C + Y
8230 CALL NUMBER ( XP, YP, 5, * H07, P10, ANGLE, =1 )
8240 16 RETURN
8250 END
```

```

3000  SUBROUTINE LOGAXS(X,Y,BCD,NC,H,SIZE,NCYL,IXY,XMIN,NA,ITIC)
3010  Z = Y
3020  G = H
3030  KCYL = NCYL
3040  KXY = IXY
3050  KA = NA
3060  KTIC = ITIC
3070  ILAB = 1
3080  XYL = ,18
3090  IF(NC)1,2,2
3100  1 ILAB = -1
3110  XYL = XYL+G
3120  2 TL = SIZE*KCYL
3130  NANG = 1-KXY
3140  NB1 = NC*ILAB
3150  LANG = (2*KXY-1)*ILAB*KTIC
3160  TICXY = LANG*0,1
3170  XTIC = TICXY*KXY
3180  YTIC = TICXY*NANG
3190  ITICM1 = 1-KTIC
3200  HO2 = G/2,
3210  HO7 = G/7,
3220  FIVHO7 = HO7*5,
3230  FH0702 = ,5*FIVHO7
3240  STITLE = ,5*TL = ,5*HO7*(7*NB1-3)
3250  XT = X
3260  YT = Z
3270  CL = SIZE
3280  ANG = 90,0*KXY
3290  ANO = ,16-KTIC*,05
3300  ANO1 = ANO+FH0702
3310  P10 = ALOG10(XMIN)
3320  P10M = P10+KCYL
3330  XPN = ,5*G
3340  IF(P10,LT,0,0,OR,P10M,GT,9,) XPN = XPN+FH0702
3350  CENTER = 5,5*HO7+XPN*KXY+NANG*HO2
3360  XAND = -ILAB*KXY*(ANO+CENTER) + CENTER
3370  YAND = ILAB*NANG*(ANO1+HO2) + HO2
3380  IF(KA)12,12,10
3390  10 XANOP = XAND+2,2*G
3400  YANOP = YAND+,7*G
3410  CALL SYMBOL(XT+XAND,YT+YAND,G,2H10,0,0,2)
3420  CALL NUMBER(XT+XANOP,YT+YANOP,FIVHO7,P10,0,0,=1)
3430  12 CALL PLOT(XT+XTIC,YT+YTIC,3)
3440  CALL PLOT(XT,YT,2)
3450  DO 60 N=1,KCYL
3460  TL = CL*(N-1)
3470  TLO2 = TL*KXY
3480  TL = TL*NANG
3490  DO 30 I=2,10
3500  FLPCOI = I
3510  TLINC = ALOG10(FLPCOI) * CL
3520  XI = TLINC*NANG
3530  XP = XI+XT+TL
3540  YI = TLINC*KXY

```

```
3550      YP = YI+YT+TLO2
3560      CALL PLOT(XP,YP,2)
3570      CALL PLOT(XP+XTIC,YP+YTIC,2)
3580  30  CALL PLOT(XP,YP,3)
3590      IF(KA) 60,60,50
3600  50  CONTINUE
3610      CALL SYMBOL(XP+XAND,YP+YAND,G,2H10,0,0,2)
3620      P10 = P10+1
3630      CALL NUMBER(XP+XANUP,YP+YANUP,FIVH07,P10,0,0,-1)
3640      CALL PLOT(XP,YP,3)
3650  60  CUNTINUE
3660      IF(G) 80,80,70
3670  70  XTITLE = KXY*(XAND+CENTER-ILAB*(CENTER+XYL)) + NANG*STITLE
3680      YTITLE = NANG*(YAND+ILAB*(G+.18)) + KXY*STITLE
3690      CALL SYMBOL(XTITLE+XT,YTITLE+YT,G,BCD,ANG,NB1)
3700  80  RETURN
3710      END
4000C
```

Instructions for PLOTLL

All input is in free-field format, and the program will call for the variables by name. The plot specification input variables are indicated in Figure B2.

Input No. 1: X \emptyset , Y \emptyset , XMIN, XCL, YMIN, YCL, IA, IDASH

X \emptyset , Y \emptyset --X and Y coordinates of the origin on the paper, in inches from the lower left of plotting surface

XMIN--starting value for X-axis in user units (lowest decade value, i.e., 0.1, 1, 10, 100, etc.)

XCL--number of inches per log-cycle on X-axis

YMIN--starting value for Y-axis in user units (0.1, 1, 10, 100, etc.)

YCL--number of inches per log cycle on Y-axis

IA--axes specification

0--plot axes

1--no axes

2--X and Y axes drawn plus lines to form right and top border

IDASH--=0, plots solid line
≠0, plots dashed line

Input No. 2: HTX, NXC, NAX

HTX--height of characters in inches for X-axis label

NXC--number of X-cycles

NAX--=1

Input No. 3: HTY, NYC, NAY

Exactly analogous to Input No. 2 except for Y-axis

Input No. 4: X-LABEL

Input No. 5: Y-LABEL

Input No. 6: SL1, SL2, BL

Input only if IDASH ≠ 0

SL1, SL2, BL--length of dashes and blank in inches

If IA = 2, the following two input specify labeling of of the right and upper axes.

Input No. 7: HTX2, NXC2, NAX2, XYO

Input No. 8: HTY2, NYC2, NAY2, YXO

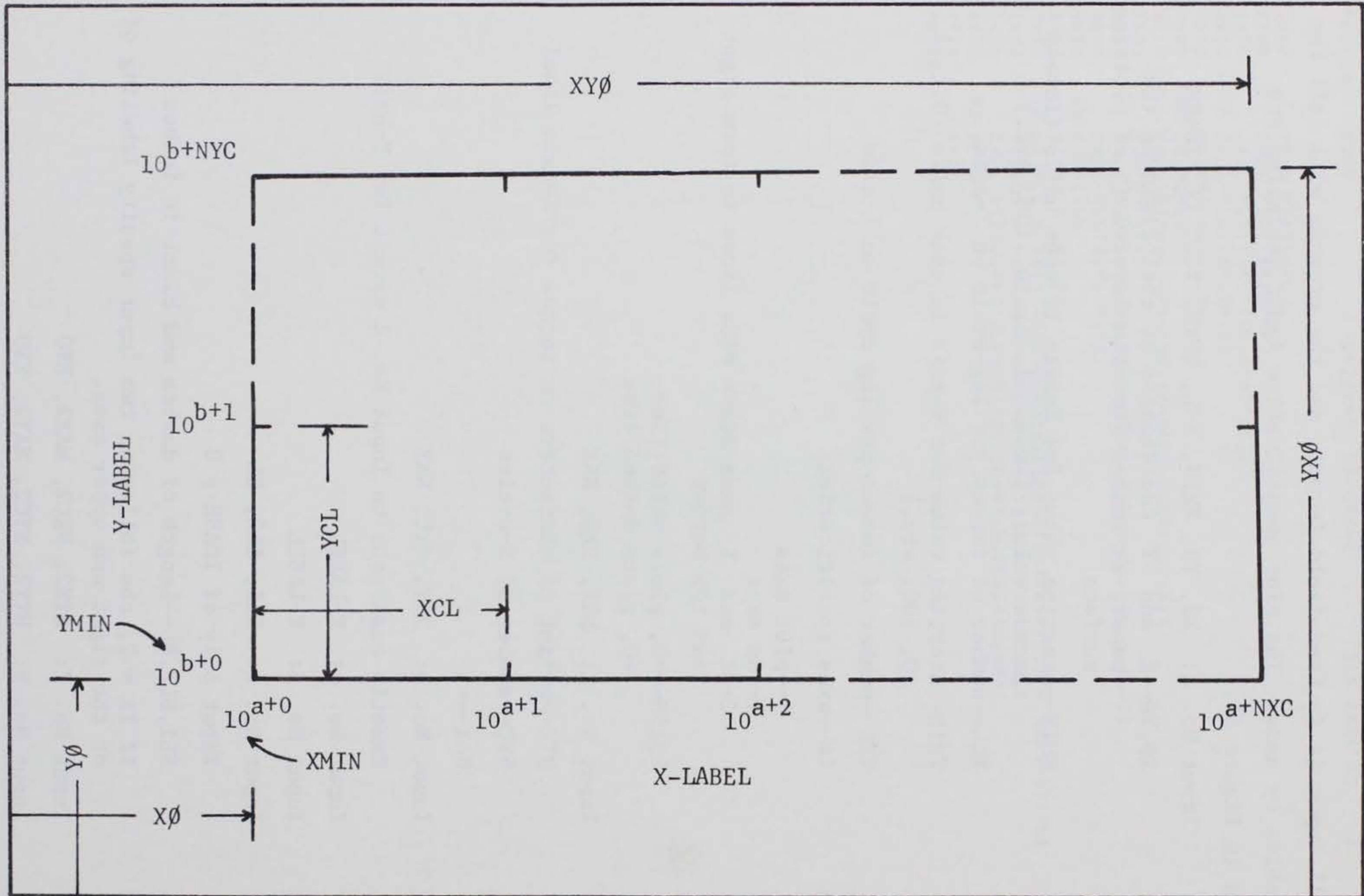


Figure B2. Definition of plot specification input parameters for PLOTLL. $X\phi$, $Y\phi$, XCL , YCL , $XY\phi$, $YX\phi$ are in inches. $XMIN$ and $YMIN$ are in user units and expressed in decimal form (i.e., .01, .1, 1, 10, 100, etc.)

HYX2,HTY2--height of characters in inches

NXC2,NYC2--number of X- and Y-cycles, respectively.

NAX2,NAY2--set both = -1

XY0,YX0--coordinates in inches of the upper right corner
of plot

```

4010***** PLOTLI *****
4020 SUBROUTINE PLOTLI(X,Y,N)
4030 COMMON /FLINP/ L1,IN
4040 DIMENSION X(1),Y(1)
4050 CHARACTER *60 LBX,LBY,LBX2,LBY2,LABT*(60),
4060 & FMT*6/6H(60A1)/,FIN*3/3H(V)/
4070 LOGICAL L1
4080 DATA L1/,T,/ , IN/5/
4090 IF(L1) PRINT,"READ X0,Y0,XMIN,XCL,YMIN,YCL,IA,IDASH"
4100 READ(IN,FIN) X0,Y0,XMIN,XCL,YMIN,YCL,IA,IDASH
4110 IF(XCL) ,99,
4120 IF(IA.EQ,1) GO TO 29
4130 LX = 01 ; LY = 1 ; LX2 = 1 ; LY2 = 01
4140 XL2 = 0. ; YL2 = 0. ; NXC2 = 0 ; NYC2 = 0
4150 IF(L1) PRINT,"READ HTX,NXC,NAX"
4160 READ(IN,FIN) HTX,NXC,NAX
4170 IF(L1) PRINT,"READ HTY,NYC,NAY"
4180 READ(IN,FIN) HTY,NYC,NAY
4190 IF(HTX.LE,0.) GO TO 7
4200 IK = 1
4210 IF(L1) PRINT,"READ X=LABEL"
4220 1 READ(IN,FMT) LABT
4230 DO 2 I=1,60
4240 K = 61-I
4250 IF(LABT(K).NE,1H ) GO TO 3
4260 2 CONTINUE
4270 3 GO TO (6,8,26,28) ,IK
4280 6 ENCODE(LBX,FMT) (LABT(I),I=1,K)
4290 LX = K
4300 7 IF(HTY.LE,0.) GO TO 9
4310 IK = 2
4320 IF(L1) PRINT,"READ Y=LABEL"
4330 GO TO 1
4340 8 ENCODE(LBY,FMT) (LABT(I),I=1,K)
4350 LY = K
4360 9 IF(IA.NE,2) GO TO 29
4370 IF(L1) PRINT,"READ HTX2,NXC2,NAX2,XY0"

```



```

4380 READ(IN,FIN) HTX2,NXC2,NAX2,XYU
4390 IF(L1) PRINT,"READ HTY2,NYC2,NAY2,YX0"
4400 READ(IN,FIN) HTY2,NYC2,NAY2,YX0
4410 IF(XY0,LE,0,) XYU = NYC2*YCL
4420 IF(YX0,LE,0,) YX0 = NXC2*XCL
4430 IF(HTX2,LE,0,) GO TO 27
4440 IK = 3
4450 IF(L1) PRINT,"READ X=LABEL2"
4460 GO TO 1
4470 26 ENCODE(LBX2,FMT) (LABT(I),I=1,K)
4480 LX2 = K
4490 27 IF(HTY2,LE,0,) GO TO 29
4500 IK = 4
4510 IF(L1) PRINT,"READ Y=LABEL2"
4520 GO TO 1
4530 28 ENCODE(LBY2,FMT) (LABT(I),I=1,K)
4540 LY2 = K
4550 29 XD = ALOG(XMIN)
4560 YD = ALOG(YMIN)
4570 XLF = .434294482*XCL
4580 YLF = .434294482*YCL
4590 IF(IDASH,NE,0) GO TO 12
4600 CALL PLOTS("A")
4610 CALL PLOT(X0,Y0,=3)
4620 DO 10 I = 1,N
4630 IF(X(I),LE,0,) X(I) = XMIN
4640 IF(Y(I),LE,0,) Y(I) = YMIN
4650 H = (ALOG(X(I))-XD)*XLF
4660 V = (ALOG(Y(I))-YD)*YLF
4670 IF(I,EG,1) CALL PLOT(H,V,3)
4680 10 CALL PLOT(H,V,2)
4690 GO TO 14
4700 12 IF(L1) PRINT,"DASHED LINE = SL1,SL2 = SOLID LENGTHS,"
4710 & " BL = BLANK LENGTH (INCHES)"
4720 IF(L1) PRINT,"READ SL1,SL2,BL"
4730 READ(IN,FIN) SL1,SL2,BL
4740 CALL PLOTS("A")
4750 CALL PLOT(X0,Y0,=3)
4760 DO 13 I=1,N
4770 IF(X(I),LE,0,) X(I) = XMIN
4780 IF(Y(I),LE,0,) Y(I) = YMIN
4790 X(I) = (ALOG(X(I))-XD)*XLF
4800 Y(I) = (ALOG(Y(I))-YD)*YLF
4810 13 CONTINUE
4820 CALL DASHED(X,Y,N,1,,1,,SL1,SL2,BL,0,)
4830 14 IF(IA=1) ,98,
4840 IF(NXC,LE,0) GO TO 16
4850 CALL LOGAXS(0,,0,,LBX,LX,HTX,XCL,NXC,0,XMIN,NAX,1)
4860 16 IF(NYC,LE,0) GO TO 17
4870 CALL LOGAXS(0,,0,,LBY,LY,HTY,YCL,NYC,1,YMIN,NAY,1)
4880 17 IF(NXC2,LE,0) GO TO 18
4890 CALL LOGAXS(0,,XY0,LBX2,LX2,HTX2,XCL,NXC2,0,XMIN,NAX2,1)
4900 18 IF(NYC2,LE,0) GO TO 98
4910 CALL LOGAXS(YX0,0,,LBY2,LY2,HTY2,YCL,NYC2,1,YMIN,NAY2,1)
4920 98 CALL PLOT(U,,0,,999)

```

```

4930 99 RETURN
4940 END
5000C

```

```

5010***** PLUTLY *****
5020 SUBROUTINE PLOTLY(X,Y,N)
5030 COMMON /FLINP/ L1,IN
5040 DIMENSION X(1),Y(1)
5050 CHARACTER *60 LBX,LBY,LBX2,LBY2,LABT*1(60),
5060 & FMT*6/6H(60A1)/,FIN*3/3H(V)/
5070 LOGICAL L1
5080 DATA L1/,T,/ , IN/5/
5090 IF(L1) PRINT,"READ X0,Y0,SFX,YMIN,YCL,IA,IDASH"
5100 READ(IN,FIN) X0,Y0,SFX,YMIN,YCL,IA,IDASH
5110 IF(SFX) ,99,
5120 SPX = 1.
5130 IF(IA,EQ,1) GO TO 29
5140 LX = -1 ; LY = 1 ; LX2 = 1 ; LY2 = -1
5150 XL2 = 0. ; YL2 = 0. ; NYC2 = 0
5160 IF(L1) PRINT,"READ HTX,XL,XS,NDX,NPX,SPX,ITX"
5170 READ(IN,FIN) HTX,XL,XS,NDX,NPX,SPX,ITX
5180 IF(SPX,LE,0.) SPX = 1. ; IF(ITX,EQ,0) ITX = 1
5190 IF(L1) PRINT,"READ HTY,NYC,NAY"
5200 READ(IN,FIN) HTY,NYC,NAY
5210 IF(HTX,LE,0.) GO TO 7
5220 IK = 1
5230 IF(L1) PRINT,"READ X=LABEL"
5240 1 READ(IN,FMT) LABT
5250 DO 2 I=1,60
5260 K = 61-I
5270 IF(LABT(K),NE,1H ) GO TO 3
5280 2 CONTINUE
5290 3 GO TO (6,8,26,28) ,IK
5300 6 ENCODE(LBX,FMT) (LABT(I),I=1,K)
5310 LX = K
5320 7 IF(HTY,LE,0.) GO TO 9
5330 IK = 2
5340 IF(L1) PRINT,"READ Y=LABEL"
5350 GO TO 1
5360 8 ENCODE(LBY,FMT) (LABT(I),I=1,K)
5370 LY = K
5380 9 IF(IA,NE,2) GO TO 29
5390 IF(L1) PRINT,"READ HTX2,XL2,XS2,NDX2,NPX2,XY0"
5400 READ(IN,FIN) HTX2,XL2,XS2,NDX2,NPX2,XY0
5410 IF(L1) PRINT,"READ HTY2,NYC2,NAY2,YX0"
5420 READ(IN,FIN) HTY2,NYC2,NAY2,YX0
5430 IF(XY0,LE,0.) XY0 = NYC2*YCL
5440 IF(YX0,LE,0.) YX0 = SPX*XL
5450 IF(HTX2,LE,0.) GO TO 27
5460 IK = 3
5470 IF(L1) PRINT,"READ X=LABEL2"
5480 GO TO 1
5490 26 ENCODE(LBX2,FMT) (LABT(I),I=1,K)
5500 LX2 = K
5510 27 IF(HTY2,LE,0.) GO TO 29
5520 IK = 4

```

```

5530     IF(L1) PRINT,"READ Y=LABEL2"
5540     GO TO 1
5550 28 ENCODE(LBY2,FMT) (LABT(I),I=1,K)
5560     LY2 = *K
5570 29 CONTINUE
5580     YU = ALOG(YMIN)
5590     XSF = SPX/SFX
5600     YLF = .434294482*YCL
5610     IF(IDASH,NE,0) GO TO 12
5620     CALL PLOTS("A")
5630     CALL PLOT(X0,Y0,=3)
5640     DO 10 I = 1,N
5650     IF(Y(I),LE,0,) Y(I) = YMIN
5660     H = X(I)*XSF
5670     V = (ALOG(Y(I))-YU)*YLF
5680     IF(I,EG,1) CALL PLOT(H,V,3)
5690 10 CALL PLOT(H,V,2)
5700     GO TO 14
5710 12 IF(L1) PRINT,"DASHED LINE = SL1,SL2 = SOLID LENGTHS,"
5720     &      " BL = BLANK LENGTH (INCHES)"
5730     IF(L1) PRINT,"READ SL1,SL2,BL"
5740     READ(IN,FIN) SL1,SL2,BL
5750     CALL PLOTS("A")
5760     CALL PLOT(X0,Y0,=3)
5770     DO 13 I=1,N
5780     IF(Y(I),LE,0,) Y(I) = YMIN
5790     X(I) = X(I)*XSF
5800     Y(I) = (ALOG(Y(I))-YU)*YLF
5810 13 CONTINUE
5820     CALL DASHED(X,Y,N,1,,1,,SL1,SL2,BL,0,)
5830 14 IF(IA=1) ,98,
5840     XS = XS*SPX
5850     IF(XL,LE,0,) GO TO 16
5860     XL = XL*SPX ; XST = XS*SFX/SPX
5870     CALL AXIS14(XS,YS,LBX,LX,HTX,XL,NDX,0,XST,SFX,SPX,
5880     &      ITX,NPX,0,)
5890 16 IF(NYC,LE,0) GO TO 17
5900     CALL LOGAXS(0,,0,,LBY,LY,HTY,YCL,NYC,1,YMIN,NAY,1)
5910 17 IF(XL2,LE,0,) GO TO 18
5920     XL2 = XL2*SPX ; XS2 = XS2*SPX
5930     XST2 = XS2*SFX/SPX
5940     CALL AXIS14(XS2,XY0,LBX2,LX2,HTX2,XL2,NDX2,0,XST2,SFX,SPX,
5950     &      ITX,NPX2,0,)
5960 18 IF(NYC2,LE,0) GO TO 98
5970     CALL LOGAXS(YX0,0,,LBY2,LY2,HTY2,YCL,NYC2,1,YMIN,NAY2,1)
5980 98 CALL PLOT(0,,0,,999)
5990 99 RETURN
6000     END

```

APPENDIX C: RESINV LISTING

RESINV

14142144 05/26/82

FILE PAGE NO. 1

```

5** RUN *;ROSD441/PLOTS,E
10     INTEGER E
20     COMMON/Z1/E,M,N/Z2/DELX,SPAC/Z3/N3/Z4/I1,RMS,RMSC/Z5/IX
30     COMMON/ZA1/Q(65,30)/ZA2/Q1(32,30)/ZA3/P(29)/ZA4/R(31),R2(31)/ZA5/
40     &R1(31),P1(29)/ZA6/SN(30)
50     DIMENSION NF(29),X(29)
60C
70C   CARD =1   ARRAY CHOICE, INPUT=
80C       1==FOR SCHLUMBERGER,
90C       2==FOR WENNER,
100C      3==FOR BIPOLE=BIPOLE,
110C   CARD =2   SPAC,E,M,NN,RMSC (FORMAT=FREE)
120C       8PAC = CLOSEST A OR S SPACING (REAL)
130C       E     = NUMBER OF MODEL LAYERS (INTEGER)
140C       M     = NUMBER OF FIELD READINGS (INTEGER)
150C       NN    = NUMBER OF FIXED PARAMETES (INTEGER)
160C       RMSC  = RMS PERCENT ERROR CUTOFF (REAL)
170C   CARD =2A  ENTER ONLY FOR BIPOLE=BIPOLE ARRAY, INPUT=
180C       1==IF N=VALUES ARE VARIED,
190C       0==IF A=SPACINGS ARE VARIED,
200C   CARD =2B  ENTER ONLY FOR BIPOLE=BIPOLE, IF VALUE ENTERED IN 2A WAS=
210C       1==INPUT N=VALUES (TOTAL M) IN INCREASING ORDER (FORMAT=FREE)
220C       0==INPUT ONE N=VALUE, (N,NE,1)
230C   CARD =3   SKIP IF 1 WAS ENTERED ON CARD =2A,INPUT=
240C       1==IF FIELD READINGS ARE PERFECTLY LOGARITHMIC ,
250C       0==OTHERWISE,
260C   CARD =3A  ENTER ONLY IF 0 WAS ENTERED ON CARD =3,
270C       INPUT A OR S=SPACINGS, (TOTAL M, FORMAT=FREE)
280C       (ENTER EXTRA CARDS IF NECESSARY,)
290C   CARD =4   ENTER FIELD APPARENT RESISTIVITY VALUES,
300C       (FORMAT=FREE, ENTER EXTRA CARDS IF NECESSARY,)
310C   CARD =5,  ENTER LAYER PARAMETERS, (TOTAL 2E-1, FORMAT=FREE)
320C       ORDER= H(1),H(2),...,H(E-1),H(1),R(2),...,R(E)
330C   CARD =6   ENTER FIXED PARAMETER NUMBERS (SKIP IF NN=0),
340C       SAME ORDER AS CARD =5,
350C       I,E, FOR 4-LAYER MODEL== IF H(3) AND R(2) FIXED, ENTER 3,5
360C   * * * * *
370C   REPEAT FOR ADDITIONAL MODELS,
380C
385   CALL FXOPT(89,1,1,0)
390   5 FORMAT(V)
400     DELX = ALOG(10,)/6,
410 1000 READ 5,INDEX
420     IF(INDEX.LE,0) STOP
430     READ 5,SPAC,E,M,NN,RMSC
440     IF(INDEX=2) 12,12,6
450   6 READ 5, IX
460     IF(IX.EQ,1) GO TO 9
470     J=1
480     GO TO 11
490   9 J=M
500  11 READ 5, (SN(I),I=1,J)
510     GO TO 512
520  12 IX=-1
530  512 N=2+E=1

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```

540     SPAC=ALOG(SPAC)
550     IF(IX,EQ,1) GO TO 13
560     READ 5, INDX1
570     IF(INDX1,EQ,1) GO TO 13
580     CALL SPLINE(M)
590     GO TO 14
600 13 READ 5, (R2(I),I=1,M)
610 14 READ 5, (P(I),I=1,N)
620     IF(NN,LE,0) GO TO 41
630     READ 5, (NF(I),I=1,NN)
640 41 PRINT 42
650 42 FORMAT(// " RESISTIVITY INVERSION PROGRAM")
660     IF(INDEX=2)43,45,47
670 43 PRINT 44
680 44 FORMAT(// " SCHLUMBERGER ARRAY"/)
690     GO TO 52
700 45 PRINT 46
710 46 FORMAT(// " WENNER ARRAY"/)
720     GO TO 52
730 47 PRINT 48
740 48 FORMAT(// " BIPOLE-BIPOLE ARRAY"/)
750     IF(IX,NE,1) GO TO 50
760     SP=EXP(SPAC)
770     PRINT 49,SP
780 49 FORMAT(/5X"BIPOLE A=SPACING ="F6,2/)
790     GO TO 52
800 50 PRINT 51,SN(1)
810 51 FORMAT(/5X"BIPOLE N=SPACING ="F6,2/)
820 52 I1=0
830     U=10,0
840     V=1,5
850 53 I1MAX = 15
860     JMAX=15
870 60 K1=0
880     J1=0
890     IF(INDEX=2) 70,80,80
900 70 CALL SCHLUM(K1)
910     GO TO 100
920 80 CALL WENBIP(K1,INDEX)
930     IF(NN,LE,0) GO TO 100
940     DO 95 I=1,NN
950         K=NF(I)
960         DO 90 J=1,M
970 90         U(J,K)=0
980 95 CONTINUE
990 100 DO 120 I=1,M
1000         R(I)=U(I,N+1)
1010         R1(I)=ALOG(R2(I)/R(I))
1020         DO 110 J=1,N
1030 110         Q(I,J)=Q(I,J)/R(I)
1040 120         CONTINUE
1050         IF(I1,GT,0) GO TO 170
1060C COMPUTE SUM OF SQUARES,
1070         PHI=0
1080         DO 130 I=1,M

```

```

1090 130 PHI=PHI+R1(I)*R1(I)
1100C COMPUTE RMS PERCENT ERROR,
1110 RMS=0
1120 DO 140 I=1,M
1130 140 RMS=RMS+(1-R(I)/R2(I))*(1-R(I)/R2(I))
1140 RMS=100.*SQRT(RMS/M)
1150 CALL OUTPUT
1160 IF(RMS.LE.RMSC) GO TO 1000
1170C COMPUTE INITIAL EPSILON,
1180 E1=0
1190 DO 160 I=1,M
1200 DO 150 J=1,N
1210 150 E1=E1+Q(I,J)*Q(I,J)
1220 160 CONTINUE
1230 E1=SQRT(E1/(M*N))
1240C ORTHOGONAL FACTORIZATION,
1250 170 CALL ORFAC1
1260 180 CALL ORFAC2(E1)
1270 CALL BACKSUB
1280 IF(NN.LE.0) GO TO 200
1290 DO 190 I=1,NN
1300 J=NF(I)
1310 190 P1(J)=0
1320 200 DO 210 I=1,N
1330 X(I)=P(I)
1340 P(I)=P(I)+P1(I)
1350 210 IF(P(I).LE.0) P(I)=0.001
1360 K1=1
1370C COMPUTE NEW MODEL APPARENT RESISTIVITIES,
1380 IF(INDEX=2) 220,230,230
1390 220 CALL SCHLUM(K1)
1400 GO TO 250
1410 230 CALL WENBIP(K1,INDEX)
1420C COMPUTE NEW SUM OF SQUARES,
1430 250 PHI1=0
1440 DO 260 I=1,M
1450 R(I)=Q(I,N+1)
1460 IF(R(I).LE.0) R(I)=0.001
1470 A=ALOG(R2(I)/R(I))
1480 260 PHI1=PHI1+A*A
1490C COMPARE NEW AND OLD SUM OF SQUARES,
1500 IF(PHI1.LT.PHI) GO TO 280
1510C INCREASE EPSILON,
1520 DO 275 I=1,N
1530 275 P(I)=X(I)
1540 E1=V*E1
1550 J1=J1+1
1560 IF(J1.LT.JMAX) GO TO 180
1570 WRITE(2,277)
1580 277 FORMAT("//" J1=JMAX,,,"TRIAL MODEL WILL NOT CONVERGE,"/)
1590 CALL OUTPUT
1600 GO TO 1000
1610 280 PHI=PHI1
1620C COMPUTE RMS PERCENT ERROR,
1630 RMS=0

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```

1640      DO 290 I=1,M
1650 290      RMS=RMS+(1-K(I)/R2(I))*(1-K(I)/R2(I))
1660      RMS=100.*SQRT(RMS/M)
1670      I1=I1+1
1680      IF(RMS.LE.RMSC) GO TO 320
1690      IF(I1.GE.I1MAX) GO TO 320
1700C COMPUTE NEW EPSILON,
1710      IF(J1) 300,300,310
1720 300 E1=E1/U
1730 310 GO TO 60
1740 320 CALL OUTPUT
1750      GO TO 1000
1760      END
1770      SUBROUTINE SCHLUM(K1)
1780      INTEGER E
1790      COMMON/Z1/E,M,N/Z2/DELX,SPAC
1800      COMMON/ZA1/Q(65,30)/ZA3/P(29)
1810      DIMENSION FLTR(29)
1820      DATA(FLTR(I),I=1,29)/.00046256,.0010907,.0017122,.0020687,
1830      &.0043048,.0021236,.015995,.017065,.048105,.21918,.64722,1.1415,
1840      &.47819,-3.515,2.7743,-1.201,.4544,-.19427,.097364,.054099,.031729
1850      &,-.019109,.011656,-.0071544,.0044042,-.002715,.0016749,-.0010335,
1860      &.00040124/
1870      Y=SPAC=19.*DELX=0.13069
1880      DO 20 I=1,M+29
1890          CALL TRANSFM(Y,I,K1)
1900 20      Y=Y+DELX
1910          J=1
1920          IF(K1.GT.0) J=N+1
1930          DO 30 I=J,N+1
1940 30      CALL FILTER(FLTR,29,I)
1950          RETURN
1960          END
1970          SUBROUTINE WENBIP(K1,INDEX)
1980          INTEGER E
1990          COMMON/Z1/E,M,N/Z2/DELX,SPAC/Z5/IX
2000          COMMON/ZA1/Q(65,30)/ZA3/P(29)/Z46/SN(50)
2010          DIMENSION FLTR(34),T(65)
2020          DATA(FLTR(I),I=1,34)/.000238935,.00011557,.00017034,.00024735,
2030      &.00036665,.00053753,.0007896,.0011584,.0017008,.0024959,.003664,
2040      &.0053773,.007893,.011583,.016498,.024934,.036556,.053507,.078121,
2050      &.11319,.16192,.22365,.28821,.30276,.15523,.32026,.53557,.71787,
2060      &.196,.054394,-.015747,.0053941,-.0021446,.000665125/
2070          S=ALOG(2.)
2080          IF(INDEX=2) 10,10,60
2090 10      Y=SPAC=10.8792495*DELX
2100          DO 55 I=1,M+33
2110              CALL TRANSFM(Y,I,K1)
2120              IF(K1.GT.0) GO TO 30
2130              DO 20 J=1,N
2140 20          T(J)=Q(I,J)
2150 30          T(N+1)=Q(I,N+1)
2160              Y1=Y+S
2170              CALL TRANSFM(Y1,I,K1)
2180              IF(K1.GT.0) GO TO 50

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```

2190      DO 40 J=1,N
2200      40      Q(I,J)=2.*T(J)=Q(I,J)
2210      50      Q(I,N+1)=2.*T(N+1)=Q(I,N+1)
2220      55      Y=Y+DELX
2230      GO TO 160
2240      60      M1=1
2250      IF(IX.NE.1) GO TO 70
2260      M1=M
2270      M=1
2280      70      DO 150 I=1,M1
2290      Y=SPAC=10.8792495*DELX
2300      A=SN(I)
2310      B=1.
2320      IF(A.LT.1.) B=A*A+A=1.
2330      A1=ABS(A=1)
2340      S1=ALOG(A1)
2350      IF(A.LT.1.) Y=Y-ALOG(A)
2360      S2=ALOG(A)
2370      S3=ALOG(A+1.)
2380      DO 140 J=1,M+33
2390      Y1=Y+S1
2400      CALL TRANSFM(Y1,J,K1)
2410      IF(K1.GT.0) GO TO 90
2420      DO 80 K=1,N
2430      80      T(K)=Q(J,K)/A1
2440      90      T(N+1)=Q(J,N+1)/A1
2450      Y1=Y+S2
2460      CALL TRANSFM(Y1,J,K1)
2470      IF(K1.GT.0) GO TO 110
2480      DO 100 K=1,N
2490      100     T(K)=T(K)=2.*Q(J,K)/A
2500      110     T(N+1)=T(N+1)=2.*Q(J,N+1)/A
2510      Y1=Y+S3
2520      CALL TRANSFM(Y1,J,K1)
2530      IF(K1.GT.0) GO TO 130
2540      DO 120 K=1,N
2550      120     Q(J,K)=(T(K)+Q(J,K)/(A+1.))*A*(A+1.)*A1/(2.*B)
2560      130     Q(J,N+1)=(T(N+1)+Q(J,N+1)/(A+1.))*A*(A+1.)*A1/(2.*B)
2570      140     Y=Y+DELX
2580      IF(IX.NE.1) GO TO 150
2590      J=1
2600      IF(K1.GT.0) J=N+1
2610      DO 145 K=J,N+1
2620      CALL FILTER(FLTH,34,K)
2630      145     Q(I+34,K)=Q(I,K)
2640      150     CONTINUE
2650      IF(IX.NE.1) GO TO 160
2660      M=M+1
2670      DO 154 I=1,M
2680      IF(K1.GT.0) GO TO 154
2690      DO 152 J=1,N
2700      152     Q(I,J)=Q(I+34,J)
2710      154     Q(I,N+1)=Q(I+34,N+1)
2720      GO TO 160
2730      160     J=1

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2740     IF(K1,GT,0) J=N+1
2750     DO 170 I=J,N+1
2760 170     CALL FILTER(FLTR,34,I)
2770 180 RETURN
2780     END
2790     SUBROUTINE TRANSFM(Y,I,K1)
2800     INTEGER E
2810     COMMON/Z1/E,M,N
2820     COMMON/ZA1/Q(65,30)/ZA3/P(29)
2830     DIMENSION T(15)
2840     U=1./EXP(Y)
2850     T(1)=P(N)
2860     IF(K1,LE,0) Q(I,N)=1.
2870     DO 30 J=2,E
2880         A=EXP(-2.*U*P(E+1=J))
2890         B=(1.-A)/(1.+A)
2900         RS=P(N+1=J)
2910         TPR=RS*B
2920         T(J)=(TPR+T(J=1))/(1.+TPR*T(J=1)/(RS*RS))
2930         IF(K1,GT,0) GO TO 30
2940         C=T(J=1)/RS
2950         D=(1.+B*C)*(1.+B*C)
2960         Q(I,N+1=J)=(B*(1.-C*C)+2.*B*T(J=1)*(T(J=1)+TPR)/(RS*RS))/D
2970         Q(I,E+1=J)=((4.*U*RS*A /((1.+A)*(1.+A)))*(1.-C*C))/D
2980         AA=(1.-B*B)/D
2990         DO 20 K=(E+2=J),E
3000             IF(K,GE,E) GO TO 20
3010             Q(I,K)=Q(I,K)*AA
3020 20         Q(I,K+E=1)=Q(I,K+E=1)*AA
3030 30     CONTINUE
3040     Q(I,N+1)=T(E)
3050     RETURN
3060     END
3070     SUBROUTINE FILTER(FLTR,K,L)
3080     INTEGER E
3090     COMMON/Z1/E,M,N
3100     COMMON/ZA1/Q(65,30)
3110     DIMENSION RES(31),FLTR(K)
3120     DO 20 I=1,M
3130         RE=0
3140         DO 10 J=1,K
3150             R=FLTR(J)*Q(I+K=J,L)
3160 10         RE=RE+R
3170 20         RES(I)=RE
3180     DO 30 I=1,M
3190 30         Q(I,L)=RES(I)
3200     RETURN
3210     END
3220     SUBROUTINE ORFAC1
3230     INTEGER E
3240     COMMON/Z1/E,M,N/Z3/N3
3250     COMMON/ZA1/Q(65,30)
3260     N3=N
3270     IF(M,EQ,N) N3=N-1
3280     DO 60 I=1,N3

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```

3290      I2=I+1
3300      S3=0
3310      DO 10 J=I,M
3320 10      S3=S3+Q(J,I)*Q(J,I)
3330      IF(S3,EQ,0) GO TO 60
3340      S3=SQRT(S3)
3350      IF(Q(I,I),GT,0) S3=-S3
3360      S4=1./SQRT(2.*S3*(S3=Q(I,I)))
3370      DO 20 J=I2,M
3380 20      Q(J,I)=-S4*Q(J,I)
3390      Q(M+1,I)=S4*(S3=Q(I,I))
3400      Q(I,I) = S3
3410      IF(I,EQ,N) GO TO 60
3420      DO 50 J=I2,N
3430      S1=Q(I,J)*Q(M+1,I)
3440      DO 30 K=I2,M
3450 30      S1=S1+Q(K,J)*Q(K,I)
3460      S1=-2.*S1
3470      Q(I,J)=Q(I,J)+S1*Q(M+1,I)
3480      DO 40 K=I2,M
3490 40      Q(K,J)=Q(K,J)+S1*Q(K,I)
3500      50      CONTINUE
3510      60      CONTINUE
3520      RETURN
3530      END
3540      SUBROUTINE ORFAC2(E1)
3550      INTEGER E
3560      COMMON/Z1/E,M,N
3570      COMMON/ZA1/Q(65,30)/ZA2/Q1(52,30)
3580      DO 80 I=1,N
3590      I2=I+1
3600      IF(I,EQ,N) GO TO 20
3610      DO 10 J=I2,N
3620 10      Q1(I,J)=0
3630 20      Q1(I,I)=E1
3640      S3=Q(I,I)*Q(I,I)
3650      DO 30 J=1,I
3660 30      S3=S3+Q1(J,I)*Q1(J,I)
3670      S3=SQRT(S3)
3680      IF(Q(I,I),GT,0) S3=-S3
3690      S4=1./SQRT(2.*S3*(S3=Q(I,I)))
3700      Q1(N+2,I)=S4*(S3=Q(I,I))
3710      DO 40 J=1,I
3720 40      Q1(J,I)=-S4*Q1(J,I)
3730      Q1(I2,I)=S3
3740      IF(I,EQ,N) GO TO 80
3750      DO 70 J=I2,N
3760      S1=Q(I,J)*Q1(N+2,I)
3770      DO 50 K=1,I
3780 50      S1=S1+Q1(K,J)*Q1(K,I)
3790      S1=-2.*S1
3800      DO 60 K=1,I
3810 60      Q1(K,J)=Q1(K,J)+S1*Q1(K,I)
3820 70      Q1(J+1,I)=Q(I,J)+S1*Q1(N+2,I)
3830 80      CONTINUE

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3840     RETURN
3850     END
3860     SUBROUTINE BACKSUB
3870     INTEGER E
3880     COMMON/Z1/E,M,N/Z3/N3
3890     COMMON/ZA1/W(65,30)/ZA2/W1(32,30)/ZA5/R1(31),P1(29)
3900     DIMENSION C(60)
3910C    CALCULATE C1,C2.
3920     DO 10 I=1,M
3930     10   C(I)=R1(I)
3940     DO 40 I=1,N3
3950     40   S1=C(I)*W(M+1,I)
3960     DO 20 J=I+1,M
3970     20   S1=S1+C(J)*W(J,I)
3980     40   S1=#2,*S1
3990     40   C(I)=C(I)+S1*W(M+1,I)
4000     DO 30 J=I+1,M
4010     30   C(J)=C(J)+S1*W(J,I)
4020     40   CONTINUE
4030C    CALCULATE C3,C2,C4.
4040     DO 50 I=1,N
4050     50   C(M+I)=0
4060     DO 80 I=1,N
4070     80   S1=W1(N+2,I)*C(I)
4080     DO 60 J=1,I
4090     60   S1=S1+C(M+J)*W1(J,I)
4100     80   S1=#2,*S1
4110     80   C(I)=C(I)+S1*W1(N+2,I)
4120     DO 70 J=1,I
4130     70   C(M+J)=C(M+J)+S1*W1(J,I)
4140     80   CONTINUE
4150C    CALCULATE DELTA=P.
4160     DO 85 I=1,N
4170     85   P1(I)=0
4180     P1(N)=C(N)/W1(N+1,N)
4190     P1(N-1)=(C(N-1)-W1(N+1,N-1)*P1(N))/W1(N,N-1)
4200     DO 100 I=3,N
4210     100  J=N-I+1
4220     100  S1=0
4230     DO 90 K=J+1,N
4240     90   S1=S1+W1(K+1,J)*P1(K)
4250     100  P1(J)=(C(J)-S1)/W1(J+1,J)
4260     RETURN
4270     END
4280     SUBROUTINE OUTPUT
4290     INTEGER E
4300     DIMENSION S2(100),C(100),SS2(100),S3(100)
4310     COMMON/Z1/E,M,N/Z2/DELX,SPAC/Z4/I1,RMS,RMSC/Z5/IX
4320     COMMON/ZA4/R(31),R2(31)/ZA3/P(29)/ZA6/SN(30)
4325     1   FORMAT(V)
4330     PRINT 100,I1
4340     100  FORMAT(///" ITERATION NO.",1X,I2//)
4350     PRINT 20
4360     20  FORMAT("LAYER NO.",6X,"THICKNESS",3X," RESISTIVITY",5X,
4370     &9MTHICK*RES,3X,9MTHICK/RES/)

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4380      DO 40 I=1,E=1
4390          J=I
4400          D1=P(I)*P(I+E=1)
4410          D2=P(I)/P(I+E=1)
4420      PRINT 30,J,P(I),P(I+E=1),D1,D2
4430      30 FORMAT(4X,I2,12X,F6.2,5X,F8.3,8X,F8.3,4X,F8.3/)
4440      40 CONTINUE
4450      PRINT 50, E,P(N)
4460      50 FURMAT(4X,I2,23X,F8.3//)
4470      IF(IX.NE.1) GO TO 56
4480      PRINT 53
4490      53 FORMAT(/18X,"N",6X,"MODEL RHO",3X,"FIELD RHO"//)
4500      GO TO 75
4510      56 X=SPAC
4520          DO 60 I=1,M
4530          SN(I)=EXP(X)
4540      60 X=X+DELX
4550      PRINT 70
4560      70 FORMAT(/15X,"SPACING",3X,"MODEL RHO",3X,"FIELD RHO"//)
4570      75 DO 90 I=1,M
4580          PRINT 80,SN(I),R(I),R2(I)
4590      80 FORMAT(14X,F8.3,3X,F8.3,3X,F8.3)
4600      90 CONTINUE
4610      PRINT 110,RMS
4620      110 FORMAT(/10X,"RMS ERROR =",F8.3//)
4621      PRINT, "PLOT INITIAL MODEL OR BEST FIT FINAL MODEL"
4623      CALL PLOT2(SN,R,M)
4624      PRINT, "DO YOU WANT TO PLOT THE FIELD DATA YES(1); NO(2)"
4625      READ 1, III
4626      IF(III.EQ.2) GO TO 120
4627      CALL PLOT2(SN,R2,M)
4628      120 CONTINUE
4630      RETURN
4640      END
4650      SUBROUTINE SPLINE(M)
4660      COMMON/Z2/DELX,SPAC
4670      COMMON/ZA4/R(31),R2(31)
4680      DIMENSION B(30),C(30),DELY(30),DELSQY(30),H(30),H2(30)
4690      DIMENSION S2(30),S3(30),SS2(31),T(31),X(31),Y(31)
4700      N=M
4710      READ 1,(X(I),I=1,N)
4720      1 FORMAT(V)
4730      DO 150 I=1,N
4740      150 X(I)=ALOG(X(I))
4750      READ 1,(Y(I),I=1,N)
4760      SPAC=X(1)
4770      M=INT((X(M)-SPAC)/DELX)+1
4780      A=SPAC
4790      DO 300 I=1,M
4800          T(I)=A
4810      300 A=A+DELX
4820      EPSLN=.00001
4830      N1=N=1
4840      DO 51 I=1,N1
4850          H(I)=X(I+1)-X(I)

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4860 51 DELY(I)=(Y(I+1)-Y(I))/H(I)
4870 DO 52 I=2,N1
4880 H2(I)=H(I-1)+H(I)
4890 B(I)=.5*H(I-1)/H2(I)
4900 DELSQY(I)=(DELY(I)-DELY(I-1))/H2(I)
4910 S2(I)=2.*DELSQY(I)
4920 52 C(I)=3.*DELSQY(I)
4930 S2(1)=0.
4940 S2(N)=0.
4950 OMEGA=1.0717968
4960 5 ETA=0.
4970 DO 10 I=2,N1
4980 W=(C(I)-B(I)*S2(I-1)-(.5*B(I))*S2(I+1)-S2(I))*OMEGA
4990 IF (ABS(W)=ETA) 10,10,9
5000 9 ETA=ABS(W)
5010 10 S2(I)=S2(I)+W
5020 IF (ETA=EPSLN) 14,5,5
5030 14 DO 53 I=1,N1
5040 53 S3(I)=(S2(I+1)-S2(I))/H(I)
5050 DO 61 J=1,M
5060 I=1
5070 IF (T(J)=X(1)) 58,17,55
5080 55 IF (T(J)=X(N)) 57,59,58
5090 56 IF (T(J)=X(I)) 60,17,57
5100 57 I=I+1
5110 GO TO 56
5120 58 WRITE(2,44) J
5130 44 FORMAT(I3,"TH ARGUMENT OUT OF RANGE")
5140 GO TO 61
5150 59 I=N
5160 60 I=I-1
5170 17 HT1=T(J)-X(I)
5180 HT2=T(J)-X(I+1)
5190 PROD=HT1*HT2
5200 SS2(J)=S2(I)+HT1*S3(I)
5210 DELSQS=(S2(I)+S2(I+1)+SS2(J))/6.
5220 R2(J)=Y(I)+HT1*DELY(I)+PROD*DELSQS
5230 61 CONTINUE
5240 RETURN
5250 END

```

APPENDIX D: RESDAT LISTING

RESDAT

14:40: 1 05/26/82

FILE PAGE NO. 1

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10** RUN *,R0SD441/PLOTS,E;R0GHG546/RESINVS,E
20   CHARACTER*72 PUS
30   DIMENSION X(100),R(100),RA(100),ASP(100),RASUM(100)
40   DIMENSION CP(100),S(100),RINV(100)
50   REAL LL,L(100)
60   PRINT 100
70   100  FORMAT('INPUT SURVEY TYPE--1= WENNER PROFILING;2= SCHLUMBERGER
80   & PROFILING; 3= WENNER SOUNDING; 4= SCHLUMBERGER SOUNDING;
90   &5= POLE= DIPOLE')
100   READ 110,I
110   110  FORMAT(V)
120   GO TO (1000,2000,3000,4000,5000),I
130C  1000 WENNER PROFILING SURVEY
140   1000 PRINT 120
150   120  FORMAT('A=SPACING=;NUMBER OF POINTS=')
160   READ 110,A,N
170   PRINT 130
180   130  FORMAT('INPUT PROFILE COORDINATE,RESISTANCE PAIRS--X1,R1,X2,R2,...')
190   READ 110,(X(I),R(I),I=1,N)
200   PRINT 140
210   140  FORMAT('IS FACTOR 2PI INCLUDED IN RESISTANCE DATA YES(1),NO(2)')
220   READ 110,IPI
230   IF(IPI,EQ,1)F=1.0
240   IF(IPI,EQ,2)F=6.28319
250   DO 150 I=1,N
260   150  RA(I)=F*R(I)*A
270   PRINT 160,A
280   160  FORMAT('WENNER PROFILE--A=',F6.1//)
290   PRINT 170
300   170  FORMAT(20X,"X",10X,"RHO")
310   PRINT 180,(X(I),RA(I),I=1,N)
320   180  FORMAT(15X,F10.4,F10.4)
330   CALL PLOT2(X,RA,N)
340   PRINT 190
350   190  FORMAT("ANOTHER PROFILE YES(1) NO(2)")
360   READ 110,II
370   IF(II,EQ,1)GOTO1000
380   IF(II,EQ,2)GOTO6000
390C  2000 SCHLUMBERGER PROFILING SURVEY
400   2000 PRINT 200
410   200  FORMAT("S=SPACING=;L=SPACING=;NUMBER OF POINTS= ")
420   READ 110,SS,LL,N
430   PRINT 130
440   READ 110,(X(I),R(I),I=1,N)
450   PRINT 140
460   READ 110, IPI
470   IF(IPI,EQ,1)F=0.5
480   IF(IPI,EQ,2)F=3.14159
490   DO 210 I=1,N
500   210  RA(I)=F*R(I)*SS*((LL/SS)**2 - 0.25)
510   PRINT 220,SS,LL
520   220  FORMAT("SCHLUMBERGER PROFILE--L=",F6.1,";S=",F6.1//)
530   PRINT 170
540   PRINT 180,(X(I),RA(I),I=1,N)
550   CALL PLOT2(X,RA,N)

```

```
560 PRINT 190
570 READ 110,II
580 IF(II,EQ,1)GOTO 2000
590 IF(II,EQ,2)GOTO 6000
600C 3000 WENNER SOUNDING SURVEY
610 3000 PRINT 230
620 230 FORMAT("INPUT SOUNDING LOCATION INFORMATION,UP TO 72 CHARACTERS")
630 READ 240,POS
640 240 FORMAT(A72)
650 PRINT 260
660 260 FORMAT("INPUT NUMBER OF DATA POINTS")
670 READ 110,N
680 PRINT 270
690 270 FORMAT("INPUT A=SPACING,RESISTANCE PAIRS--A1,R1,A2,R2,...")
700 READ 110,(ASP(I),R(I),I=1,N)
710 PRINT 140
720 READ 110,IPI
730 IF(IPI,EQ,1)F=1.0
740 IF(IPI,EQ,2)F=6.28319
750 DO 280 I=1,N
760 280 RA(I)= F*ASP(I)*R(I)
770 PRINT 290,POS
780 290 FORMAT("WENNER SOUNDING"//A72//)
790 PRINT 300
800 300 FORMAT(16X,"A",8X,"RHO")
810 PRINT 310,(ASP(I),RA(I),I=1,N)
820 310 FORMAT(10X,F10.4,F10.4)
830 PRINT,"DO YOU WANT LINEAR(TYPE 1) OR LOG-LOG(TYPE 2) PLOTS"
840 READ 110,III
850 IF(III,EQ,2) GO TO 313
860 CALL PLOT2(ASP,RA,N)
870 GO TO 315
880 313 CALL PLOTLL(ASP,RA,N)
890 315 PRINT,"DO YOU WANT A CUMULATIVE SUM PLOT YES(1),NO(2)"
900 READ 110, KK
910 IF(KK,EQ,2) GO TO 319
920 RASUM(1)=RA(1)
930 DO 317 I=2,N
940 RASUM(I)=RASUM(I-1)+RA(I)
950 317 CONTINUE
960 PRINT 318,RASUM(N)
970 318 FORMAT("MAX. CUMULATIVE RESISTIVITY VALUE = ",F8.2)
980 PRINT,"PLOT CUMULATIVE RESISTIVITY VS. A=SPACING DATA"
990 CALL PLOT2(ASP,RASUM,N)
1000 PRINT,"DO YOU WANT AN INVERSE RESISTIVITY PLOT YES(1),NO(2)"
1010 READ 110,KKK
1020 IF(KKK,EQ,2) GO TO 319
1030 DO 325 I=1,N
1040 325 RINV(I)=1./(F*R(I))
1050 PRINT 316, RINV(N)
1060 316 FORMAT("//MAX. VALUE OF INVERSE RESISTIVITY = ",F10.6//)
1070 CALL PLOT2(ASP,RINV,N)
1080 319 PRINT 320
1090 320 FORMAT("DO YOU WISH TO INTERPRET DATA YES(1), NO(2)")
1100 READ 110,JJ
```

```
1110     IF(JJ,EQ,2) GO TO 6000
1120     INDE=2
1130     SPA=ASP(1)
1140     INDX=0
1150     CALL RESINVS(ASP,RA,N,INDE,SPA,INDX)
1160     PRINT 330
1170 330  FORMAT("ANOTHER SOUNDING YES(1), NO(2)")
1180     READ 110,JJ
1190     IF(JJ,EQ,1) GO TO 3000
1200     IF(JJ,EQ,2) GO TO 6000
1210C 4000     SCHLUMBERGER SOUNDING
1220 4000 PRINT 230
1230     READ 240,POS
1240     PRINT 140
1250     READ 110, IPI
1260     IF(IPI,EQ,1) F=0.5
1270     IF(IPI,EQ,2) F=3.14159
1280 4010 PRINT 4020
1290 4020 FORMAT("INPUT NO. OF DATA POINTS")
1300     READ 110, N
1310     PRINT 4030
1320 4030 FORMAT("INPUT S=SPACING, L=SPACING, RESISTANCE DATA")
1330     READ 110,(S(I),L(I),R(I), I=1,N)
1340     DO 4040 I=1,N
1350 4040 RA(I)=F*R(I)*S(I)*((L(I)/S(I))**2 - 0.25)
1360     PRINT 4045, POS
1370 4045 FORMAT(///"SCHLUMBERGER SOUNDING"//A72//)
1380     PRINT 4050
1390 4050 FORMAT(20X,"S",5X,"L",10X,"RHO")
1400     PRINT 4060,(S(I),L(I),RA(I), I=1,N)
1410 4060 FORMAT(16X,F5.1,2X,F6.1,6X,F10.4)
1420     PRINT,"DO YOU WANT TO PLOT APPARENT RESISTIVITY VS. L=SPACING"
1430     PRINT,"LINEAR(TYPE 1) OR LOG=LOG(TYPE 2)"
1440     READ 110, NNN
1450     IF(NNN,EQ,2) GO TO 4065
1460     CALL PLOT2(L,RA,N)
1470     GO TO 4067
1480 4065 CALL PLOTLL(L,RA,N)
1490 4067 PRINT,"DO YOU WANT TO INTERPRET DATA YES(1),NO(2)----"
1500     & IF SO, ONLY ONE S-VALUE SHOULD BE IN DATA OR THERE SHOULD
1510     & BE NO JUMPS IN THE SOUNDING CURVE"
1520     READ 110, III
1530     IF(III,EQ,1) GO TO 4080
1540 4070 PRINT,"DO YOU WANT TO INPUT DATA FOR ANOTHER SOUNDING"
1550     READ 110,JJJ
1560     IF(JJJ,EQ,1) GO TO 4000
1570     GO TO 6000
1580 4080 CONTINUE
1590     INDE=1
1600     SPA=L(1)
1610     INDX=0
1620     CALL RESINVS(L,RA,N,INDE,SPA,INDX)
1630     GO TO 4070
1640 5000 CONTINUE
1650C     POLE=DIPOLE SURVEY
```



```
1660 PRINT 5010
1670 5010 FORMAT('POLE=DIPOLE CURRENT STATION/PROFILE DIRECTION INFORMATION
1680 & UP TO 72 CHARACTERS')
1690 READ 240, POS
1700 PRINT 140
1710 READ 110, IPI
1720 IF (IPI, EQ, 1) F=1.0
1730 IF (IPI, EQ, 2) F=6.28319
1740 PRINT 5020
1750 5020 FORMAT('INPUT POTENTIAL ELECTRODE SPACING AND NUMBER OF
1760 & DATA VALUES')
1770 READ 110, PP, N
1780 PRINT, "INPUT==DISTANCE TO FIRST POTENTIAL ELECTRODE, RESISTANCE
1790 & PAIRS"
1800 READ 110, (CP(I), R(I), I=1, N)
1810 PRINT, 'POLE=DIPOLE SURVEY'
1820 PRINT 5025, POS
1830 5025 FORMAT('//A72//')
1840 PRINT 5027
1850 5027 FORMAT(14X, 'C1P1, C1P2', 10X, 'RHO'//)
1860 DO 5030 I=1, N
1870 RA(I)=(F*CP(I)*(CP(I)+PP)/PP)*R(I)
1880 PRINT 5040, CP(I), CP(I)+PP, RA(I)
1890 5030 CONTINUE
1900 5040 FORMAT(10X, F0.1, F0.1, 5X, F10.4)
1910 PRINT, "PLOT APPARENT RESISTIVITY VERSUS X=X AT MIDPOINTS
1920 & OF PP=LOCATIONS"
1930 DO 5050 I=1, N
1940 5050 X(I)=CP(I)+PP/2
1950 CALL PLOT2(X, RA, N)
1960 PRINT, "DO YOU WANT TO INPUT ANOTHER DATA SET"
1970 READ 110, II
1980 IF (II, EQ, 1) GO TO 5000
1990 IF (II, EQ, 2) GO TO 6000
2000 6000 CONTINUE
2010 STOP
2020 END
```

APPENDIX E: TIDES LISTING

TIDES

14:28:20 05/26/82

FILE PAGE NO. 1

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5** RUN *;R03D441/PLOTS,E
10C THIS PROGRAM COMPUTES THE THEORETICAL GRAVITY TIDE FOR ANY POINT
20C ON THE SURFACE OF A RIGID EARTH AS A FUNCTION OF TIME.
30C A COMPLIANCE FACTOR OF 1.16 HAS BEEN INCLUDED.
40C INPUT DATA ARE IN FREE FIELD FORMAT.
50C INPUT DATA IDENTIFIED BY COMMENTS JUST PRIOR TO READ STATEMENTS.
60C
65     CHARACTER *8XINPUT(3)
70     DIMENSION DAYPM(12),G(5000)
72     REAL MINUTE(5000)
75     DATA XINPUT(1),XINPUT(3)/1H/,1H;/
80     DOUBLE PRECISION CDEGTR,CMINTR,CSECTR,PI2,SC1,PC1,HC1,ANC1,S,P,H,
90     &P1,AN,STOR,T,SMINP,S2HP,SMINH,HMINP1,SMINP2,SMINH2,CHI,CHI1,ALSUN,
100    &ALPHA,XI,SIGMA,ALMOON,ARG6,ARG7,ARG9,ARG10,E1,E11,E12,E13,C,U,
110    &APRIME,APRIM1,DISTES,DISTEM,DAYS1,DAYS2,DAYS3,DAYS4,DAYS5,DAYS6
115    M=0
120    CDEGTR=1.7453292519943D=2
130    CMINTR=2.90888208666D=4
140    CSECTR=4.848136811D=6
150    DATA C,C1,E/3.84402D10,1.495D13,.05490/
160    DATA AMU,AMMOON,AMSUN/6.670E=8,7.3537E25,1.993E33/
170    DATA E11,E12,E13/1.675104D=2,4.180D=5,1.26D=7/
180    RATIO=.074804
190    OMEGA=23.452*CDEGTR
200    SMALLA=6.37827E8
240    PI2=6.2831853072D0
250    SC1=1108411.2D0
260    PC1=392515.94D0
270    HC1=129602768.13D0
280    ANC1=482912.63D0
313C  INPUT NAME OF OUTPUT DATA FILE
325    CALL ATTACH(4,XINPUT,3,0,,)
326    80 FORMAT (V)
328C  INPUT NUMBER OF TIDE DATA SETS(NCOMP) AND TIME INCREMENT(MM)
330    READ 10, NCOMP,MM
340    DO 400 JJ=1,NCOMP
350    PRINT 10, JJ
353C  INPUT LATITUDE IN DEGREES(SLATD) AND DECIMAL MINUTES(SLATM) AND
354C  SIMILARLY FOR LONGITUDE(SLONGD,SLONGM). INPUT ELEVATION IN
355C  METERS(SELEV). INPUT DATE IN MONTH(DATEM), DAY(DATED, AND
357C  YEAR(DATEY). INPUT STARTING TIME IN HOUR(TIMEH) AND MINUTE(TIMEM)
358C  GREENWICH TIME.
360    READ 20, SLATD,SLATM,SLONGD,SLONGM,SELEV,DATEM,DATED,DATEY,TIMEH
370    &,TIMEM
375C  INPUT TOTAL NUMBER OF TIME INCREMENTS TO BE CALCULATED(NTOTAL)
376C  THUS THE TOTAL LENGTH OF TIDAL RECORD TO BE CALCULATED=MM X NTOTAL
380    READ 10, NTOTAL
385    WRITE (4,5) NTOTAL
390    DO600 KK=1,NTOTAL
400    IF(KK,EG,1) GO TO 75
410    MINUTE(KK)=MINUTE(KK=1)+MM
420    DAYS5=MINUTE(KK)/(24.*60.)
430    GO TO 350
440    75 DAYS2=0.
450    ALAMBDA=SLATD*CDEGTR+SLATM*CMINTR

```

```

460     ALONG=SLONGD+SLONGM/60.
470     ELEV=SELEV*100.
480     MONTH=DATEM
490     IDAY=DATED
500     IYEAR=DATEY
510     IHOUR=TIMEH
520     MINUTE(KK)=TIMEM
530C    CALCULATE T (NUMBER OF JULIAN CENTURIES)
540     DATA DAYPM/31,,28,,31,,30,,31,,30,,31,,31,,30,,31,,30,,31./
550     DO 100 I=1,12
560     JS=MONTH=I
570     IF(JS,EQ,0) GO TO 150
580 100  DAYS2=DAYS2+DAYPM(I)
590 150  DAYS3=IDAY=1
600     DAYS4=IHOUR/24.
610     DAYS5=MINUTE(KK)/(24.*60.)
620     DAYS1=IYEAR*365.
630     NYEAR=IYEAR/4
640     SJ=IYEAR/4.-NYEAR
650     IF(SJ,GT,0) GO TO 200
660     IF(MONTH=2) 300,300,200
670 200  DAYS6=NYEAR
680     GO TO 350
690 300  DAYS6=NYEAR-1.
700 350  CONTINUE
710     STOR=DAYS1+DAYS2+DAYS3+DAYS4+DAYS5+DAYS6+.5
720     T=STOR/36525.
730     S=270.D0*CDEGTR+26.D0*CMINTR+14.72D0*CSECTR+((.0068D0*CSECTR*T+
740     &9.09D0*CSECTR)*T+1336.D0*PI2+SC1*CSECTR)*T
750     P=334.D0*CDEGTR+19.D0*CMINTR+40.87D0*CSECTR+(((=.045D0)*CSECTR*T
760     &=37.24D0*CSECTR)*T+11.D0*PI2+PC1*CSECTR)*T
770     H=279.D0*CDEGTR+41.D0*CMINTR+48.04D0*CSECTR+(1.089D0*CSECTR*1+
780     &HC1*CSECTR)*T
790     AN=259.D0*CDEGTR+10.D0*CMINTR+57.12D0*CSECTR+((.008D0*CSECTR*T+
800     &7.58D0*CSECTR)*T+5.D0*PI2+ANC1*CSECTR)*T
810     P1=281.D0*CDEGTR+13.D0*CMINTR+15.D0*CSECTR+((.012D0*CSECTR*T+
820     &1.63D0*CSECTR)*T+6189.03D0*CSECTR)*T
830     E1=E11=(E12+E13*T)*T
840     ARG1=1./(1.+006738*(SIN(ALAMBDA)**2))
850     CAPC=SQRT(ARG1)
860     RADIUS=CAPC*SMALLA+ELEV
870     APRIME=1./(C*(1.-E**2))
880     APRIM1=1./(C1*(1.-E1**2))
890     SMINP=S=P
900     S2HP=S=2*H+P
910     SMINH=S=H
920     HMINP1=H=P1
930     SMINP2=2.*SMINP
940     SMINH2=2.*SMINH
950     DISTEM=1./C+APRIME*E*DCOS(SMINP)+APRIME*(E**2)*DCOS(SMINP2)
960     &+15*APRIME*RATIO*E*DCOS(S2HP)/8.+APRIME*(RATIO**2)*DCOS(SMINH2)
970     DISTES=1./C1+APRIM1*E1*DCOS(HMINP1)
980     TZERO=IHOUR+MINUTE(KK)/60.
990     SMALLT=(15.*(TZERO-12.)-ALONG)*CDEGTR
1000    CHI1=SMALLT+H

```

```

1010  ALSUN=H+2.*E1*DSIN(HMINP1)
1020  ARG2=5.145*CDEGTH
1030  ARG3=COS(OMEGA)*COS(ARG2)-SIN(OMEGA)*SIN(ARG2)*DCOS(AN)
1040  AI=ARCCOS(ARG3)
1050  ARG4=SIN(ARG2)*DSIN(AN)/SIN(AI)
1060  ANU=ARCSIN(ARG4)
1070  CHI=SMALLT+H-ANU
1080  SALPHA=SIN(OMEGA)*DSIN(AN)/SIN(AI)
1090  CALPHA=DCOS(AN)*COS(ANU)+DSIN(AN)*SIN(ANU)*COS(OMEGA)
1100  CALPH1=1+CALPHA
1110  ALPHA=2*ATAN2(SALPHA,CALPH1)
1120  XI=AN-ALPHA
1130  SIGMA=S-XI
1140  ALMOON=SIGMA+2.*E*DSIN(SMINP)+5.*(E**2)*DSIN(SMINP2)/4.
1150  &+15.*RATIO*E*DSIN(SZHP)/4.+11.*(RATIO**2)*DSIN(SMINH2)/8.
1160  ARG5=(OMEGA/2.)
1170  ARG6=ALSUN-CHI1
1180  ARG7=ALSUN+CHI1
1190  CPHI=SIN(ALAMBD)*SIN(OMEGA)*DSIN(ALSUN)+COS(ALAMBD)*((COS(ARG5)**2
1200  &*DCOS(ARG6)+(SIN(ARG5)**2)*DCOS(ARG7))
1210  ARG8=(AI/2.)
1220  ARG9=ALMOON-CHI
1230  ARG10=ALMOON+CHI
1240  CTHETA=SIN(ALAMBD)*SIN(AI)*DSIN(ALMOON)+COS(ALAMBD)*((COS(ARG8)**2
1250  &)*DCOS(ARG9)+(SIN(ARG8)**2)*DCOS(ARG10))
1260  GM=AMU*AMMOON*RADIUS*(3.*(CTHETA**2)-1.)*(DISTEM**3)+3*(AMU*AMMOON
1270  &*(RADIUS**2)*(5.*(CTHETA**3)-3.*CTHETA))*(DISTEM**4)/2.
1280  GM=GM*1000.
1290  GS=AMU*AMSUN*RADIUS*(3.*(CPHI**2)-1)*(DISTES**3)*1000.
1300  GZERO=GM+GS
1305  G(KK)=GZERO*1160.
1306  M=M+1
1310  600 WRITE(4,90) M,MINUTE(KK),G(KK)
1320  PRINT65, SLATD,SLATM,SLONGD,SLONGM ,DATEM,DATED,DATEY,TIMEH,
1330  &TIMEM
1340  PRINT 70, (G(LL), LL=1,NTOTAL)
1345  CALL PLOT2(MINUTE,G,NTOTAL)
1350  400 CONTINUE
1355  5  FORMAT(I4)
1360  10  FORMAT(V)
1370  20  FORMAT(V)
1380  50  FORMAT(3F15.5)
1400  65  FORMAT(1X,F3.0,F5.2,F4.0,F5.2,5F3.0)
1410  70  FORMAT('0',12F6.1,/12F6.1)
1415  90  FORMAT(I3,I5,F15.3)
1420  STOP
1430  END

```

APPENDIX F: TALGRAD LISTING

TALGRAD

14:45: 1 05/26/82

FILE PAGE NO. 1

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10** RUN *;R0SD441/PLOTS,E
20C TALGRAD COMPUTES GRAVITY AND GRAVITY GRADIENT PROFILES OVER TWO=
30C DIMENSIONAL POLYGONAL CROSS=SECTION MODELS
40   DIMENSION XXX(40),XX(200),X(40),Z(40),R(40),A(40),B(40),
50   &S(40),U(40),V(40),T(40),W(40),GG(40),GTC(10,200),GTT(10,200),
60   &BA(200),M(10),DELGTZ(200),DELGTX(200)
70   DIMENSION G(200),XHG(200),AS(200)
75   DIMENSION DELGTZP(200)
80   PRINT , "K, DELX, DELZ, ZMAX"
90   READ 10, K, DELX, DELZ, ZMAX
100 10  FORMAT(V)
110   DO 20 M=1, K
120 20  XX(M)=DELX*(M-1)
130   PRINT , "NPOLY"
140   READ 30, NPOLY
150 30  FORMAT(V)
160   PRINT 40
170 40  FORMAT("DIMENSION IN KFT(TYPE 1) OR METERS(TYPE 2)")
180   READ 50, NN
190 50  FORMAT(V)
200   IF(NN, EQ, 1) C=4.067
210   IF(NN, EQ, 2) C=13.34E=3
220   DO 70 II=1, 10
230   DO 60 NG=1, 200
240 60  GTT(II, NG)=0.0
250 70  CONTINUE
260   M(1)=0.0
270   DO 1000 II=1, 10
280   DO 295 L=1, NPOLY
283   PRINT 73, L
285 73  FORMAT("POLYGON==", I2/)
290   PRINT, "DELRO, N"
300  READ 80, DELRO, N
310 80  FORMAT(V)
320   PRINT , "X1, Z1, . . . ., XN, ZN"
330   READ 100, (XXX(M), Z(M), M=1, N)
340 100 FORMAT(V)
350   IF(II, GT, 1) GO TO 145
360   PRINT 110
370 110 FORMAT("//25X, "STATIONS   POLYG. SIDES   DENSITY"/)
380   PRINT 120, K, N, DELRO
390 120 FORMAT(I30, I10, F20.6//)
400   PRINT 130
410 130 FORMAT(21X, 6HVERTEX, 7X, 12HDISTANCE   , 9X, 9HDEPTH   )
420   PRINT 140, (M, XXX(M), Z(M), M=1, N)
430 140 FORMAT(I25, 2F20.6)
440 145 NN=N+1
450   XXX(NN)=XXX(1)
460   Z(NN)=Z(1)
470 150 DO 160 NG=1, 200
480 160 GTC(II, NG)=0.0
490   DO 290 NG=1, K
500   DO 170 I=1, NN
510   X(I)=XXX(I)-XX(NG)
520 170 CONTINUE

```

```

530      DO 280 J=1,N
540      JJ=J+1
550      H(J)=X(J)**2+(Z(J)+H(II))**2
560      R(JJ)=X(JJ)**2+(Z(JJ)+H(II))**2
570      A(J)=X(JJ)-X(J)
580      B(J)=Z(JJ)-Z(J)
590      S(J)=X(J)*(Z(JJ)+H(II))-X(JJ)*(Z(J)+H(II))
600      U(J)=A(J)**2 + B(J)**2
610      V(J)=0.5*ALOG(R(JJ)/R(J))
620      T(J)=X(J)*X(JJ)+(Z(J)+H(II))*(Z(JJ)+H(II))
630      IF(S(J)) 180,250,200
640 180  IF(T(J)) 190,230,220
650 190  W(J)=3.1415927 + ATAN(S(J)/T(J))
660      GO TO 260
670 200  IF(T(J)) 210,240,220
680 210  W(J)=3.1415927 + ATAN(S(J)/T(J))
690      GO TO 260
700 220  W(J)=ATAN(S(J)/T(J))
710      GO TO 260
720 230  W(J)=1.570796
730      GO TO 260
740 240  W(J)=1.570796
750      GO TO 260
760 250  W(J)=0.0
770 260  GG(J)=(S(J)/U(J))*(B(J)*V(J)-A(J)*W(J))
780 270  GPA=C*DELRO*GG(J)
790      GTC(II,NG)=GTC(II,NG)+GPA
800 280  CONTINUE
810      GTT(II,NG)=GTT(II,NG)+GTC(II,NG)
820      G(NG)=GTT(II,NG)
830 290  CONTINUE
840 295  CONTINUE
850      PRINT 300, H(II)
860 300  FORMAT('DO YOU WANT TO PRINT GZ FOR H=',F6.2,'--YES(1),NO(2)')
870      READ 30,MM
880      IF(MM,EW,2) GO TO 305
890      PRINT 310, H(II)
900 310  FORMAT('-----ELEVATION = ',F10.6,'-----')
910      PRINT 320
920 320  FORMAT(15X,'STATION',10X,'X',10X,'GZ(X)',/)
930      DO 1500 NG=1,K
940 1500  PRINT 330,NG,XX(NG),GTT(II,NG)
950 330  FORMAT(17X,I3,8X,F10.6,5X,F10.6)
960 305  CONTINUE
961      PRINT, 'DO YOU WANT PLOTS OF GRAVITY PROFILES--YES(1), NO(2)'
962      READ 10, NN
963      IF(NN,EW,2) GO TO 333
970      PRINT 331,H(II)
980 331  FORMAT('PLOT GRAVITY PROFILE FOR H=',F6.2/)
990      CALL PLOT2(XX,G,K)
1000 333  IF(H(II),GE,ZMAX) GO TO 340
1010      H(II+1)=H(II)+DELZ
1020 1000  CONTINUE
1030 340  PRINT 350
1040 350  FORMAT('DO YOU WANT TO CALCULATE GRAVITY GRADIENTS

```

```

1050      &TYPE 1 FOR YES, 2 FOR NO)
1060      READ 360, NGRAD
1070 360  FORMAT(V)
1080      IF(NGRAD, EQ, 2) GO TO 5000
1090 365  PRINT 370
1100 370  FORMAT('INPUT DESIRED INCREMENT VALUES FOR HORIZONTAL AND'/
1110      &'VERTICAL GRADIENT VALUES, DELXX AND DELZZ, IN INCREMENTS'/
1120      &'OF DELX AND DELZ==')
1130      READ 380, DELXX, DELZZ
1140 380  FORMAT(V)
1150      IX=DELXX/DELX
1160      IF(DELZ, EQ, 0, 0) GO TO 505
1170      IZ=DELZZ/DELZ
1180      DO 2500 NG=1, K
1190 2500 DELGTZ(NG)=(GTT(1, NG)-GTT(IZ+1, NG))/DELZZ
1200      PRINT 390, DELZZ
1210 390  FORMAT('====DELTA=Z = ', F10, 6//15X, 'STATION', 10X, 'GZ, Z'//)
1220      DO 400 NG=1, K
1230 400  PRINT 500, NG, XX(NG), DELGTZ(NG)
1240 500  FORMAT(17X, I3, 8X, F10, 6, 5X, F10, 6)
1250      PRINT 502
1260 502  FORMAT('PLOT VERTICAL GRADIENT PROFILES')
1270      CALL PLOT2(XX, DELGTZ, K)
1280 505  PRINT 510
1290 510  FORMAT('INPUT VALUE OF H FOR WHICH THE HORIZONTAL GRADIENT'/
1300      &'IS DESIRED IN INCREMENT OF DELZ')
1310      READ 520, HZ
1320 520  FORMAT(V)
1330      NZ=HZ/DELZ
1340      IF(DELZ, EQ, 0, 0, OR, HZ, EQ, 0, 0) NZ=1
1350      DO 3000 NG=1, K-IX
1360      DELGTX(NG)=(GTT(NZ, IX+NG)-GTT(NZ, NG))/DELXX
1370      IF(IX+NG+1, GT, K) GO TO 530
1380 3000  CONTINUE
1390 530  PRINT 540, DELXX
1400 540  FORMAT('====DELTA=X = ', F10, 6//15X, 'STATION', 10X,
1410      &'GZ, X'//)
1420      DO 550 NG=1, K
1430      PRINT 560, NG, IX+NG, DELGTX(NG)
1440      XHG(NG)=(XX(IX+NG)+XX(NG))/2.
1450      IF(IX+NG+1, GT, K) GO TO 551
1460 550  CONTINUE
1470 551  PRINT 553
1480 553  FORMAT('PLOT HORIZONTAL GRADIENT PROFILE==PLOTTED AT MIDPOINTS'/
1490      &'OF DELXX INTERVALS')
1500      KK=K-IX
1510      CALL PLOT2(XHG, DELGTX, KK)
1520 560  FORMAT(15X, I3, ', ', I3, 6X, F10, 6, 5X, F10, 6)
1530      PRINT 562
1540 562  FORMAT('DO YOU WANT GRADIENT SPACE AND SQ. OF MODULUS OF ANALYTIC'/
1550      &'SIGNAL PLOTS ***IF SO, IX MUUST EQUAL 2*** YES(1), NO(2)')
1560      READ 580, MMM
1570      IF(MMM, EQ, 2) GO TO 570
1580      DO 565 I=1, K
1590      DELGTZP(I)=DELGTZ(I+1)

```

```
1600 IF(I+1, EQ, K=1) GO TO 567
1610 565 CONTINUE
1620 567 CONTINUE
1630 DO 568 I=1, KK
1640 568 AS(I) = DELGTX(I)**2 + DELGTZP(I)**2
1650 CALL PLOT2(DELGTZP, DELGTX, KK)
1660 CALL PLOT2(XHG, AS, KK)
1670 570 CONTINUE
1680 PRINT, "DO YOU WANT TO RECALCULATE GRADIENTS FOR OTHER VALUES OF"
1690 PRINT, "DELXX AND DELZZ YES(1), NO(2)"
1700 READ 580, NNN
1710 580 FORMAT(V)
1720 IF(NNN, EQ, 1) GO TO 365
1730 5000 CONTINUE
1740 STOP
1750 END
```


APPENDIX G: HILBERT LISTING

MILBERT

141471 5 05/26/82

FILE PAGE NO. 1

```

10*# RUN *,R0SD441/PLOTS,E
20   DIMENSION T(100),H(100),X(100)
30   DIMENSION A(100)
40   READ 10,N,DELX
45   X(1)=.5*DELX
50   DO 7 I=2,N
60   7 X(I)=X(I-1) + DELX
70   READ 10, (T(I), I=1,N)
90  10 FORMAT(V)
100  DO 20 I=1,N
110  CALL MILBRT(T,N,H,A)
120  20 CONTINUE
130  PRINT 25
140  25 FORMAT(10X,"X",12X,"GZ,X",12X,"GZ,Z",12X,"A")
150  PRINT 30,(X(I),T(I),H(I),A(I),I=1,N)
160  30 FORMAT(5X,F10.4,F15.8,F15.8,F15.8)
170  PRINT, "DO YOU WANT GRADIENT PROFILES YES(1), NO(2)"
180  READ 10, MM
190  IF(MM,EQ,2) GO TO 33
200  CALL PLOT2(X,H,N)
210  CALL PLOT2(X,T,N)
220  33 PRINT, "DO YOU WANT A GRADIENT SPACE PLOT YES(1), NO(2)"
230  READ 10, NN
240  IF(NN,EQ,2) GO TO 35
250  CALL PLOT2(H,T,N)
260  35 PRINT, "DO YOU WANT A PLOT OF THE MODULUS OF THE ANALYTIC
270  & SIGNAL YES(1), NO(2)"
280  READ 10, LL
290  IF(LL,EQ,2) GO TO 40
295  CALL PLOT2(X,A,N)
300  40 STOP
310  END
320  SUBROUTINE MILBRT(T,N,H,A)
330  DIMENSION T(1),H(1),A(1)
340  DO 5 I=1,N
350  5 T(N+2-I)=T(N+1-I)
360  T(1)=0
370  T(N+2)=0
380  DO 40 I=1,N
390  H(I)=0
400  J=1
410  10 IF(J,EQ,(N-I+1)) GO TO 20
420  H(I)=H(I)+(T(I+J+1)*(J+1)-T(I+J+2)*J)*ALOG(1,+1./J)
430  J=J+1
440  GO TO 10
450  20 J=1
460  30 IF(J,EQ,I) GO TO 40
470  H(I)=H(I)+(T(I-J)*J-T(I-J+1)*(J+1))*ALOG(1,+1./J)
480  J=J+1
490  GO TO 30
500  40 H(I)=H(I)/3.141593
510  DO 45 I=1,N
520  T(I)=T(I+1)
530  45 A(I)=T(I)**2 + H(I)**2
540  RETURN

```

MILBERT CONT

141471 5 05/26/82

FILE PAGE NO. 2

550 END

APPENDIX H: SEISDIG, SEISPLOT,
REFINT, AND DOMER LISTINGS

SEISDIG 1

```

LIS
10 INIT
20 REM*****
30 REM** THIS PROGRAM IS DESIGNED TO REDUCE SEISMIC REFRACTION *****
40 REM** OSCILLOGRAPH RECORDS, AND WRITE THE RESULTING TIME- *****
50 REM** DISTANCE INFORMATION TO A MAGNETIC TAPE *****
60 REM*****
100 PAGE
110 PRINT "INPUT FROM THE KEYBOARD IDENTIFICATION OF DATA"
120 PRINT "THIS INFORMATION MUST BE 72 CHARACTERS OR LESS"
130 INPUT X$
140 DIM G(24),T(24)
150 PRINT "INPUT COORDINATE OF SHOTHOLE IN FEET."
160 INPUT S1
170 PRINT "INPUT DISTANCE FROM SHOTHOLE TO GEOPHONE NEAREST IT."
180 PRINT "NOTE--USE NEGATIVE # IF MOVING FROM HIGH FOOTAGE TO "
190 PRINT "LOW FOOTAGE."
200 INPUT G(1)
210 PRINT "KEY IN THE SHOTHOLE DEPTH"
220 INPUT D2
230 G(1)=G(1)+S1
240 PRINT "INPUT THE SPACING BETWEEN GEOPHONES--USE NEGATIVE VALUE"
250 PRINT "IF MOVING FROM HIGH FOOTAGE TO LOW FOOTAGE."
260 INPUT S
270 REM*****
280 REM** INITIALIZE OSCILLOGRAPH RECORD *****
290 REM*****
300 PRINT "DIGITIZE THE TIMING LINE JUST PRECEDING THE TIME BREAK"
310 INPUT @8:T1,D,D1
320 PRINT "G"
330 PRINT "DIGITIZE THE TIMING LINE OCCURING 200 msec LATER"
340 INPUT @8:T2,D,D1
350 PRINT "G"
360 T3=200/(T2-T1)
370 PRINT "DIGITIZE THE TIME BREAK"

380 INPUT @8:T0,D,D$
390 PRINT "G"
400 PAGE
410 PRINT "DIGITIZE THE FIRST ARRIVALS OFF OSCILLOGRAPH RECORD"
420 PRINT " 1. PRESS WHITE BUTTON NORMALLY."
430 PRINT " 2. PRESS BUTTON #1 IF A TRACE IS SKIPPED"
440 PRINT " 3. PRESS BUTTON #2 TO REDIGITIZE THE PRECEDING POINT"
450 PRINT " 4. PRESS BUTTON #3 TO DIGITIZE LAST POINT"
460 N=1
470 PRINT @32,26:2
480 PRINT "DIGITIZE TRACE # ";N
490 INPUT @8:T(N),Y,Z$
500 PRINT "GGG"
510 T(N)=(T(N)-T0)*T3
520 IF Z$="2" THEN 600
530 IF Z$="4" THEN 480
540 IF Z$="8" THEN 560
550 GO TO 570
560 G(N)=G(N)+S
570 G(N+1)=G(N)+S
580 N=N+1
590 GO TO 480
600 REM*****
610 REM**CORRECT DISTANCES FOR SHOTHOLE DEPTH USING PYTHAGOREAN*****
620 REM**THEOREM APPLIED TO FIRST FOUR GEOPHONES AND THEN *****
630 REM**LIST THE TIME DISTANCE INFORMATION *****
640 REM*****
650 D3=D2^2
660 FOR I=1 TO 4
670 L1=ABS(S1-G(I))^2
680 IF S>0 THEN 710
690 G(I)=S1-SQR(L1+D3)
700 GO TO 720
710 G(I)=S1+SQR(L1+D3)
720 NEXT I

```

SEISDIG 2

```

730 PAGE
740 Y$="
750 Y$=Y$&Y$
760 P=LEN(X$)
770 O=36-P/2
780 Y$=REP(X$,O,P)
790 PRINT Y$
800 PRINT @32,26:0
810 A$="TRACE NO."
820 B$="DISTANCE"
830 C$="TIME(msec)"
840 PRINT A$,B$,C$
850 PRINT "-----"
860 PRINT
870 FOR I=1 TO N
880 PRINT I,G(I),T(I)
890 NEXT I
900 INPUT U$
910 PAGE
920 PRINT "WOULD YOU LIKE TO REDIGITZE ANY OF THE POINTS?"
930 INPUT Q$
940 IF Q$="N" THEN 1040
950 PRINT "WHICH POINT NO."
960 INPUT I
970 PRINT "DIGITIZE THE POINT"
980 INPUT @8:T(I),Y,Z$
990 T(I)=(T(I)-T0)*T3
1000 GO TO 920
1010 REM*****
1020 REM*****STORE DATA ON MAGNETIC TAPE*****
1030 REM*****
1040 PAGE
1050 PRINT "WOULD YOU LIKE TO STORE THIS TIME-DISTANCE INFO ON TAPE?"
1060 INPUT Q$
1070 IF Q$="N" THEN 1160

```

SEISDIG 4 (Last)

```

1080 PRINT "WHICH FILE # WOULD YOU LIKE TO STORE DATA ON?"
1090 INPUT F1
1100 FIND F1
1110 WRITE @33:X$
1120 WRITE @33:N
1130 FOR I=1 TO N
1140 WRITE @33:G(I),T(I)
1150 NEXT I
1160 END

```

```

LIS
1 INIT
3 S9=0
4 L9=1.636363
5 L8=1
6 DIM T(50),D(50)
7 REM : TO USE THIS PROGRAM FOR PAPER PLOTS - SET CORNERS ON PLOTTER
8 REM : TO DEFAULT VALUES OF 10" BY 15" - IT IS DESIGNED TO PLOT
9 REM : AN X AXIS OF 7" AND A Y AXIS OF 5" ON PAPER WHICH IS 8"x 10.5"
10 REM : IN SIZE - WHEN MOUNTING PAPER ON PLOTTER SET LEFT EDGE OF
11 REM : PAPER IN LINE WITH THE SCREWS ON THE LEFT HAND SIDE OF THE
12 REM : PLOTTING SURFACE
19 PAGE
20 PRINT "KEY IN THE PROPER # TO PERFORM THE INDICATED FUNCTION"
30 PRINT "      1      ENTER DATA"
40 PRINT "      2      CHANGE OR ADD DATA"
50 PRINT "      3      PLOT DATA AND LABEL AXES"
60 PRINT "      4      CHOOSE BETWEEN PAPER OR CRT PLOT"
61 PRINT "      5      DISPLAY DATA"
62 PRINT "      6      SELECT SYMBOL"
69 PRINT "      7      STORE DATA ON TAPE"
70 PRINT "      8      READ DATA FROM TAPE"
71 PRINT "      9      STOP PROGRAM"
80 PRINT "INPUT THE APPROPRIATE NUMBER"
85 DIM T(50),D(50)
90 INPUT M1
95 PRINT @1,17:1,1.636363
100 GO TO M1 OF 130,320,430,520,220,1550,1610,1800,1530
110 DIM T(50),D(50)
120 PAGE
130 PRINT "INPUT TIME DEPTH VALUES, END LIST WITH TIME LESS THAN ZERO"
140 J1=1
150 PRINT "DISTANCE(";J1;") = ";
160 INPUT T(J1)
162 IF T(J1)<0 THEN 210

```

```

170 PRINT "TIME(";J1;") = ";
180 INPUT D(J1)
190 J1=J1+1
200 GO TO 150
210 J1=J1-1
220 PAGE
230 E$="POINT NO."
240 D$="TIME (MSEC)"
250 F$="DEPTH (MSEC)"
260 PRINT E$,F$,D$
270 PRINT
280 PRINT
290 FOR I=1 TO J1
300 PRINT I,T(I),D(I)
310 NEXT I
320 PRINT "WOULD YOU LIKE TO CHANGE OR ADD ANY POINTS (ANSWER Y OR N)???"
330 INPUT Q$
340 IF Q$="Y" THEN 360
350 GO TO 19
360 PRINT "KEY IN THE POINT NO."
370 INPUT I
380 PRINT "KEY IN THE CORRECTED OR ADDED POINT VALUES"
390 INPUT T(I),D(I)
400 IF I<J1 THEN 420
410 J1=I
420 GO TO 220
430 PAGE
440 PRINT "WHAT ARE X AND Y SCALE FACTORS?"
450 INPUT X2,Y2
451 X1=7*X2
452 Y1=5*Y2
460 PRINT "WHAT IS THE X LABEL?"
470 INPUT X$
480 PRINT "WHAT IS THE Y LABEL?"
490 INPUT Y$

```

```

500 PRINT "WHAT IS THE BORING HOLE NUMBER?"
510 INPUT B$
520 PRINT "FOR PAPER PLOT TYPE 1; FOR CRT PLOT TYPE 32"
530 INPUT N0
535 PRINT "WOULD YOU LIKE TO PLOT THE AXIS (ANSWER Y OR N)"
536 INPUT C$
540 PRINT @1,17:1,1.636363
541 PRINT "WOULD YOU LIKE TO PLOT ON GRAPH PAPER (ANSWER Y OR N)"
542 INPUT G$
543 IF G$="N" THEN 550
544 PRINT "MOVE PEN TO ORIGIN AND PRESS CALL BUTTON ON PLOTTER"
545 INPUT @1,27:X3,Y4,G$
546 X4=X3+70
547 Y3=Y4+50
548 GO TO 640
550 X3=18
560 X4=88
570 Y3=61
580 Y4=11
590 GO TO 640
600 X3=45
610 X4=105
620 Y3=85
630 Y4=15
640 PAGE
650 VIEWPORT X3,X4,Y4,Y3
660 WINDOW 0,X1,0,Y1
665 IF C$="N" THEN 680
670 AXIS @N0:X2/2,Y2/2
675 AXIS @N0:X2/2,Y2/2,X1,Y1
680 GOSUB 1390
690 REMARK
700 REMARK TIC LABEL SECTION
705 IF C$="Y" THEN 720
707 GO TO 1331

```

```

710 REMARK
720 FOR I=0 TO X1 STEP X2
730 WINDOW 0,X1,0,Y1
740 MOVE @N0:I,0
750 IF I=0 THEN 790
760 L1=LGT(I)
770 L1=INT(L1+1.0E-3)+1
780 GO TO 800
790 L1=1
800 SCALE 1,1
810 RMOVE @N0:-L1/2*L8-L8,-L9
820 PRINT @N0:I
830 NEXT I
840 WINDOW 0,X1,0,Y1
850 VIEWPORT X3,X4,Y4,Y3
860 MOVE @N0:X1/2,0
870 SCALE 1,1
880 RMOVE @N0:0,5
890 M=LEN(X$)/2
900 RMOVE @N0:-L8*M,-6*L9
910 PRINT @N0:X$
920 FOR J=0 TO Y1 STEP Y2
930 WINDOW 0,X1,0,Y1
940 MOVE @N0:0,J
950 IF J=0 THEN 990
960 L2=LGT(J)
970 L2=INT(L2+1.0E-3)
980 GO TO 1000
990 L2=0
1000 SCALE 1,1
1010 RMOVE @N0:-L8*(L2+3),-0.5*L8
1020 PRINT @N0:J
1030 NEXT J
1040 REMARK
1050 REMARK*****Y AXIS*****

```

```

1060 REMARK
1070 WINDOW 0,X1,0,Y1
1080 MOVE @N0:0,Y1/2
1090 SCALE 1,1
1100 L=LEN(Y$)/2
1110 IF N0=32 THEN 1140
1120 RMOVE @N0:-4*L9,-L
1130 GO TO 1150
1140 RMOVE @N0:-5*L9,L*2
1150 FOR I=1 TO LEN(Y$)
1160 A$=SEG(Y$,I,1)
1170 PRINT @N0,25:90
1180 PRINT @N0:A$;
1190 IF N0=32 THEN 1220
1210 GO TO 1230
1220 RMOVE @N0:0,-2.82
1230 NEXT I
1240 HOME
1250 REMARK
1260 REMARK*****PRINT THE TITLE*****1000 REMARK
1270 WINDOW 0,X1,0,Y1
1280 MOVE @N0:X1/2,Y1
1290 SCALE 1,1
1300 C$=H$
1310 RMOVE @N0:L8*(-LEN(C$)/2),4*L9
1320 PRINT @N0,25:0
1330 PRINT @N0:C$
1331 WINDOW 0,150,0,100
1332 VIEWPORT 0,150,0,100
1333 MOVE @1:X3,Y4
1340 INPUT Z$
1350 GO TO 19
1360 REMARK*****
1370 REMARK PLOT DATA POINTS WITH TRIANGLES
1380 REMARK*****

1390 WINDOW 0,X1,0,Y1
1400 VIEWPORT X3,X4,Y4,Y3
1410 MOVE @N0:0,0
1420 FOR I=1 TO J1
1430 MOVE @N0:T(I),D(I)
1440 DRAW @N0:T(I),D(I)
1450 S1=X1/70*1.25
1460 S2=Y1/70*1.25
1461 IF S9<>1 AND S9<>2 THEN 1510
1462 IF S9=2 THEN 1502
1470 RMOVE @N0:S1/2,S2/3
1480 RDRAW @N0:-S1/2,-S2
1490 RDRAW @N0:-S1/2,S2
1500 RDRAW @N0:S1,0
1501 GO TO 1510
1502 REM:::::::::: PLOT SQUARES ::::::::::::::
1503 RMOVE @N0:S1/2,-S2/2
1504 RDRAW @N0:0,S2
1505 RDRAW @N0:-S1,0
1506 RDRAW @N0:0,-S2
1507 RDRAW @N0:S1,0
1510 NEXT I
1520 RETURN
1530 END
1540 IF N0=32 THEN 1180
1550 PAGE
1560 PRINT "CHOOSE AND KEY IN THE APPROPRIATE SYMBOL NO."
1570 PRINT "      1 FOR TRIANGLE"
1580 PRINT "      2 FOR SQUARE"
1590 INPUT S9
1600 GO TO 19
1610 REM: STORE DATA ON TAPE
1620 PRINT "TYPE IN IDENTIFICATION"
1630 INPUT N$
1640 PRINT "INPUT FILE # THAT YOU WANT DATA STORED ON"

```

```

1650 INPUT F3
1660 FIND F3
1670 WRITE N$
1680 WRITE J1
1690 FOR L=1 TO J1
1700 WRITE T(L),D(L)
1710 NEXT L
1720 GO TO 19
1800 REM: READ DATA FROM TAPE
1810 PRINT "INPUT FILE # DATA IS TO BE READ FROM"
1820 INPUT F3
1825 FIND F3
1830 READ @33:N$
1840 READ @33:J1
1850 FOR L=1 TO J1
1860 READ @33:T(L),D(L)
1870 NEXT L
1880 GO TO 19

```

REFINT 1

```

LIS
90 DIM X(4,2),U(4,2),D(4,2),S1(2),A$(1),U2(4),T(4,2)
100 PRINT "WOULD YOU LIKE TO PROCESS BOTH A FORWARD AND REVERSE LINE?"
110 INPUT A$
120 IF A$="Y" THEN 190
130 F1=1
140 PRINT "IS THE LINE BEING PROCESSED FORWARD OF REVERSE (TYPE F OR R)"
150 INPUT A$
160 IF A$="F" THEN 200
170 F1=3
180 GO TO 200
190 F1=2
200 PRINT "TYPE IN LINE IDENTIFICATION"
210 INPUT B$
220 PRINT "DIGITIZE THE FOLLOWING INFORMATION FROM THE T-D PLOT"
230 PRINT "JDIGITIZE THE ORIGIN"
240 INPUT @8:A0,B0,M$
250 PRINT "G"
260 PRINT "JDIGITIZE THE RIGHTMOST POINT ON THE HORIZONTAL AXIS"
270 INPUT @8:A2,B2,M$
280 PRINT "G"
290 PRINT "JDIGITIZE THE HIGHEST POINT ON THE VERTICAL AXIS"
300 INPUT @8:A4,B4,M$
310 PRINT "G"
320 REMARK:*****
330 REMARK:      INITIALIZE VARIABLES
340 REMARK:*****
350 L1=0
360 L2=0
370 FOR I=1 TO 4
380 FOR J=1 TO 2
390 X(I,J)=0
400 U(I,J)=0
410 T(I,J)=0
420 D(I,J)=0

```

```

430 NEXT J
440 NEXT I
450 IF F1=3 THEN 490
460 PRINT "HOW MANY LAYERS ARE ASSOCIATED WITH THE FORWARD LINE?"
470 INPUT L1
480 IF F1=1 THEN 520
490 PRINT "HOW MANY LAYERS ARE ASSOCIATED WITH THE REVERSE LINE?"
500 INPUT L2
510 IF F1=3 THEN 630
520 PRINT "DIGITIZE CRITICAL DISTANCES ON THE FORWARD LINE"
530 FOR I=1 TO L1
540 IF I=L1 THEN 570
550 PRINT "DIGITIZE CRITICAL DISTANCE #";I
560 GO TO 580
570 PRINT "DIGITIZE ANY POINT ON THE HIGHEST FORWARD VELOCITY LINE"
580 INPUT @8:X(I,1),T(I,1),M$
590 PRINT "G"
600 NEXT I
610 IF F1=1 THEN 720
620 PAGE
630 PRINT "DIGITIZE CRITICAL DISTANCES ON REVERSE LINE:"
640 FOR I=1 TO L2
650 IF I=L2 THEN 680
660 PRINT "CRITICAL DISTANCE #";I
670 GO TO 690
680 PRINT "DIGITIZE ANY POINT ON THE HIGHEST REVERSE VELOCITY LINE"
690 INPUT @8:X(I,2),T(I,2),M$
700 PRINT "G"
710 NEXT I
720 PAGE
730 IF F1=3 THEN 780
740 PRINT "FROM THE KEYBOARD ENTER THE FOLLOWING INFORMATION:"
750 PRINT "DISTANCE OF FORWARD SHOTPOINT FROM ORIGIN"
760 INPUT S1(1)
770 IF F1=1 THEN 810

```

```

780 PRINT "DISTANCE OF REVERSE SHOTPOINT FROM THE ORIGIN"
790 INPUT S1(2)
800 IF F1=3 THEN 840
810 PRINT "INPUT THE FORWARD SHOTHOLE DEPTH"
820 INPUT D8
830 IF F1=1 THEN 860
840 PRINT "INPUT THE REVERSE SHOTHOLE DEPTH"
850 INPUT D9
860 A1=0
870 B1=0
880 PRINT "THE MAXIMUM VALUE OF THE HORIZONTAL AXIS"
890 INPUT A3
900 PRINT "THE MAXIMUM VALUE ON THE VERTICAL AXIS"
910 INPUT B5
920 A=A2-A0
930 B=B4-B0
940 REMARK*****
950 REMARK: FORWARD CALCULATIONS MADE IN THE NEXT SECTION
960 REMARK*****
970 IF F1=3 THEN 1060
980 FOR I=1 TO L1
990  $X(I,1)=(X(I,1)-A0)/A*(A3-A1)$ 
1000  $T(I,1)=(T(I,1)-B0)/B*(B5-B1)$ 
1010  $X(I,1)=ABS(X(I,1)-S1(1))$ 
1020 NEXT I
1030 REMARK:*****
1040 REMARK: CALCULATIONS FOR REVERSE LINE
1050 REMARK:*****
1060 IF F1=1 THEN 1150
1070 FOR I=1 TO L2
1080  $X(I,2)=(X(I,2)-A0)/A*(A3-A1)$ 
1090  $T(I,2)=(T(I,2)-B0)/B*(B5-B1)$ 
1100  $X(I,2)=ABS(X(I,2)-S1(2))$ 
1110 NEXT I
1120 REMARK:*****

```



```

1130 REMARK: COMPUTE VELOCITIES
1140 REMARK:*****
1150 FOR I=1 TO 2
1160 IF F1=3 AND I=1 OR (F1=1 AND I=2) THEN 1180
1170 V(I,I)=(X(I,I)-A1)/(T(I,I)-B1)*1000
1180 NEXT I
1190 IF F1=3 THEN 1240
1200 FOR I=2 TO L1
1210 V(I,1)=(X(I,1)-X(I-1,1))/(T(I,1)-T(I-1,1))*1000
1220 NEXT I
1230 IF F1=1 THEN 1280
1240 FOR I=2 TO L2
1250 V(I,2)=(X(I,2)-X(I-1,2))/(T(I,2)-T(I-1,2))*1000
1260 NEXT I
1270 REMARK:*****
1280 REMARK: COMPUTE DEPTHS
1290 REMARK:*****
1300 IF F1=3 THEN 1380
1310 D(1,1)=X(1,1)/2*SQR((V(2,1)-V(1,1))/(V(2,1)+V(1,1)))+D8/2
1320 IF L1=2 THEN 1370
1330 D(2,1)=5/6*D(1,1)+X(2,1)/2*SQR((V(3,1)-V(2,1))/(V(3,1)+V(2,1)))
1340 IF L1=3 THEN 1370
1350 D1=1/6*D(1,1)+3/4*D(2,1)
1360 D(3,1)=D1+X(3,1)/2*SQR((V(4,1)-V(3,1))/(V(4,1)+V(3,1)))
1370 IF F1=1 THEN 1440
1380 D(1,2)=X(1,2)/2*SQR((V(2,2)-V(1,2))/(V(2,2)+V(1,2)))+D9/2
1390 IF L2=2 THEN 1440
1400 D(2,2)=5/6*D(1,2)+X(2,2)/2*SQR((V(3,2)-V(2,2))/(V(3,2)+V(2,2)))
1410 IF L2=3 THEN 1440
1420 D2=1/6*D(1,1)+3/4*D(2,2)
1430 D(3,2)=D2+X(3,2)/2*SQR((V(4,2)-V(3,2))/(V(4,2)+V(3,2)))
1440 REMARK*****
1450 REMARK: OUTPUT SECTION RESULTS ARE NOW COMPLETE
1460 REMARK*****
1470 IF L1>L2 OR F1=1 OR F1=3 THEN 1540

```

```

1480 REMARK*****
1490 REMARK: COMPUTE TRUE VELOCITIES
1500 REMARK:*****
1510 FOR I=1 TO L1
1520 V2(I)=2*V(I,1)*V(I,2)/(V(I,1)+V(I,2))
1530 NEXT I
1540 PAGE
1550 PRINT B$
1560 PRINT "J"
1570 PRINT " FORWARD REVERSE"
1580 PRINT USING 1590:
1590 IMAGE 11X, "-----", 25X, "-----"
1600 PRINT "J"
1610 PRINT USING 1620:
1620 IMAGE 22X, "THE CRITICAL DISTANCES ARE:"
1630 PRINT "J"
1640 L=L1
1650 IF L1>L2 THEN 1670
1660 L=L2
1670 FOR I=1 TO L-1
1680 PRINT USING 1690: I, X(I,1), I, X(I,2)
1690 IMAGE 11X, "X(", 1D, ") =", 6D, 18X, "X(", 1D, ") =", 6D
1700 NEXT I
1710 PRINT "J"
1720 PRINT USING 1730:
1730 IMAGE 22X, "THE APPARENT VELOCITIES ARE:"
1740 FOR I=1 TO L
1750 PRINT USING 1760: I, V(I,1), I, V(I,2)
1760 IMAGE 11X, "V(", 1D, ") =", 6D, " fps", 17X, "V(", 1D, ") =", 6D, " fps"
1770 NEXT I
1780 PRINT "J"
1790 PRINT USING 1800:
1800 IMAGE 11X, "THE CALCULATED DEPTHS ARE:"
1810 PRINT "J"
1820 FOR I=1 TO L-1

```

```

1830 PRINT USING 1840:I,D(I,1),I,D(I,2)
1840 IMAGE 11X,"D(",1D,") =",3D.2D , " ft",18X,"D(",1D,") =",3D.2D," ft"
1850 NEXT I
1860 IF L1<>L2 OR F1=1 OR F1=3 THEN 1960
1870 PRINT "J"
1880 PRINT USING 1890:
1890 IMAGE 22X,"THE TRUE VELOCITIES ARE:"
1900 PRINT "J"
1910 FOR I=1 TO L
1920 PRINT USING 1930:I,U2(I)
1930 IMAGE 11X,"U(",1D,") =",6D
1940 NEXT I
1950 GO TO 1970
1960 PRINT "JJTHE TRUE VELOCITIES WERE NOT COMPUTED FOR THIS CASE"
1970 END

```

+

LIST

```

10 INIT
15 REM DOMER<DIGITIZATION OF MULTI-EVENT REFRACTION DATA>-DEY
16 REM PROGRAM WILL DIGITIZE PEAK ARRIVAL TIME AND 1 CYCLE OF
17 REM EACH EVENT. IT WILL HANDLE UP TO 5 EVENTS PER TRACE FOR 24
18 REM TRACES. CALCULATES FREQ&GROUP VELOCITY AND OUTPUTS IN TABLE
19 REM GEOPHONES MUST BE EQUALLY SPACED. T/D PLOT OF PK FOR ALL EVENTS.
20 DIM T1(24),T2(24),T3(24),T4(24),T5(24),D(24)
30 DIM F1(24),F2(24),F3(24),F4(24),F5(24),H1(24),H2(24)
35 S9=0
37 F9=0
40 T1=-1
45 T2=-1
50 T3=-1
55 T4=-1
60 T5=-1
65 F1=T1
70 F2=T2
75 F3=T3
80 F4=T4
90 F5=T5
110 PRINT "ENTER TITLE"
120 INPUT T$
130 PRINT "ENTER GEOPHONE SPACING"
140 INPUT X
150 PRINT "ENTER TIME INTERVAL TO BE DIGITIZED"
160 INPUT R
170 PRINT "DIGITIZE TIME INTERVAL"
180 INPUT @8:T8,Z,Z$
190 PRINT "G"
200 INPUT @8:T9,Z,Z$
210 PRINT "G"
220 S6=R/(T9-T8)
225 PRINT "DIGITIZE ZERO TIME"
227 INPUT @8:T7,Z,Z$

```

DOMER 1

```

228 PRINT "G"
230 PRINT "ENTER NUMBER OF EVENTS TO BE DIGITIZED"
240 INPUT N
250 FOR M=1 TO N
260 PRINT "ENTER STARTING TRACE NUMBER"
270 INPUT C
280 FOR K=C TO 24
290 PRINT "DIGITIZE EVENT#";M;" TRACE ";K;" PEAK"
300 INPUT @8:T,Z,Z$
305 T=(T-T7)*S6
310 GOSUB 900
320 PRINT "DIGITIZE EVENT#";M;" TRACE ";K;" LEFT TROUGH"
330 INPUT @8:L,Z,Z$
340 GOSUB 900
350 PRINT "DIGITIZE EVENT#";M;" TRACE ";K;" RIGHT TROUGH"
360 INPUT @8:R,Z,Z$
370 GOSUB 900
380 P=1/((R-L)*S6)
385 P=INT(P*10000)/10
390 GOSUB 600
400 NEXT K
410 NEXT M
420 REM:::OUTPUT DATA
430 M=1
440 H1=T1
450 H2=F1
460 GOSUB 800
470 M=M+1
480 IF M>N THEN 590
490 H1=T2
500 H2=F2
510 GOSUB 800
520 M=M+1
530 IF M>N THEN 590
540 H1=T3

```

```

550 H2=F3
560 GOSUB 800
570 IF M>N THEN 590
572 H1=T4
574 H2=F4
576 GOSUB 800
579 M=M+1
580 IF M>N THEN 590
582 H1=T5
584 H2=F5
586 GOSUB 800
590 PRINT "ALL EVENTS PRINTED **NORMAL TERMINATION***"
595 GO TO 4000
600 REM:::SUBR DATA ARRAY SORT:::
610 GO TO M OF 630,660,690,720,750
620 PRINT "SORT ERROR"
630 T1(K)=T
640 F1(K)=P
650 RETURN
660 T2(K)=T
670 F2(K)=P
680 RETURN
690 T3(K)=T
700 F3(K)=P
710 RETURN
720 T4(K)=T
730 F4(K)=P
740 RETURN
750 T5(K)=T
760 F5(K)=P
770 RETURN
800 REM:::SUBR OUTPUT DATA TABLE:::
805 PRINT " " "IT$
806 PRINT " "
810 PRINT "EVENT NUMBER ";M

```

```

812 PRINT
815 PRINT " X, ft          T, msec          F, hz          Ug, ft/s"
820 PRINT "-----"
825 FOR K=1 TO 24
830 S=K*X
835 IF H1(K)=-1 THEN 860
836 H1(K)=INT(H1(K)*10)/10
840 U=S/H1(K)
842 U=INT(U*10000)/10
845 PRINT S, H1(K), H2(K), U
850 GO TO 870
860 PRINT S
870 NEXT K
875 COPY
880 PAGE
885 GOSUB 2000
890 RETURN
900 REM:::SUBR FLAG SORT::
910 PRINT "G"
915 PAGE
920 IF Z$="4" THEN 290
930 IF Z$="8" THEN 400
940 IF Z$="2" THEN 410
950 RETURN
1000 STOP
2000 REM:::SUBR PLOT::
2010 L9=1.63636
2020 L8=1
2040 REM TO USE THIS PROGRAM FOR PAPER PLOTS - SET CORNERS ON PLOTTER
2050 REM:TO DEFAULT VALUES OF 10" BY 15" - IT IS DESIGNED TO PLOT
2060 REM:AN X AXIS OF 7" AND A Y AXIS OF 5" ON PAPER WHICH IS 8"x 10.5"
2070 REM: IN SIZE - WHEN MOUNTING PAPER ON PLOTTER SET LEFT EDGE OF

```

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2130 PAGE
2135 IF F9=1 THEN 2210
2140 PRINT "WHAT ARE X AND Y SCALE FACTORS?"
2150 INPUT X2, Y2
2160 X1=7*X2
2170 Y1=5*Y2
2180 X$="DISTANCE, ft."
2190 Y$="TIME, msec."
2200 N0=1
2210 GOSUB 3405
2230 PRINT @1, 17:1, 1.636363
2240 X3=18
2250 X4=88
2260 Y3=61
2270 Y4=11
2330 PAGE
2340 VIEWPORT X3, X4, Y4, Y3
2350 WINDOW 0, X1, 0, Y1
2360 IF F9=1 THEN 3140
2370 AXIS @N0: X2/2, Y2/2
2380 AXIS @N0: X2/2, Y2/2, X1, Y1
2400 REMARK
2410 REMARK TIC LABEL SECTION
2440 REMARK
2450 FOR I=0 TO X1 STEP X2
2460 WINDOW 0, X1, 0, Y1
2470 MOVE @N0: I, 0
2480 IF I=0 THEN 2520
2490 L1=LGT(I)
2500 L1=INT(L1+1.0E-3)+1
2510 GO TO 2530
2520 L1=1
2530 SCALE 1, 1
2540 RMOVE @N0: -L1/2*L8-L8, -L9
2550 PRINT @N0: I

```

```

2560 NEXT I
2570 WINDOW 0,X1,0,Y1
2580 VIEWPORT X3,X4,Y4,Y3
2590 MOVE @N0:X1/2,0
2600 SCALE 1,1
2610 RMOVE @N0:0,5
2620 M9=LEN(X$)/2
2630 RMOVE @N0:-L8*M9,-6*L9
2640 PRINT @N0:X$
2650 FOR J=0 TO Y1 STEP Y2
2660 WINDOW 0,X1,0,Y1
2670 MOVE @N0:0,J
2680 IF J=0 THEN 2720
2690 L2=LGT(J)
2700 L2=INT(L2+1.0E-3)
2710 GO TO 2730
2720 L2=0
2730 SCALE 1,1
2740 RMOVE @N0:-L8*(L2+3),-0.5*L8
2750 PRINT @N0:J
2760 NEXT J
2770 REMARK
2780 REMARK*****Y AXIS*****
2790 REMARK
2800 WINDOW 0,X1,0,Y1
2810 MOVE @N0:0,Y1/2
2820 SCALE 1,1
2830 L=LEN(Y$)/2
2850 RMOVE @N0:-4*L9,-L
2880 FOR I=1 TO LEN(Y$)
2890 A$=SEG(Y$,I,1)
2900 PRINT @N0,25:90
2910 PRINT @N0:A$;
2950 NEXT I
2960 HOME

```

```

2970 REMARK
2980 REMARK*****PRINT THE TITLE*****1000 REMARK
2990 WINDOW 0,X1,0,Y1
3000 MOVE @N0:X1/2,Y1
3010 SCALE 1,1
3020 C$=T$
3030 RMOVE @N0:L8*(-LEN(C$)/2),4*L9
3040 PRINT @N0,25:0
3050 PRINT @N0:C$
3060 WINDOW 0,150,0,100
3070 VIEWPORT 0,150,0,100
3080 MOVE @1:X3,Y4
3090 REM::?INPUT Z$??
3095 F9=1
3110 REMARK*****
3120 REMARK PLOT DATA POINTS WITH TRIANGLES
3130 REMARK*****
3140 WINDOW 0,X1,0,Y1
3150 VIEWPORT X3,X4,Y4,Y3
3160 MOVE @N0:0,0
3170 FOR I=1 TO 24
3180 D(I)=I*10
3185 IF H1(I)<0 THEN 3360
3190 MOVE @N0:D(I),H1(I)
3200 DRAW @N0:D(I),H1(I)
3210 S1=X1/70*1.25
3220 S2=Y1/70*1.25
3230 IF S9<>1 AND S9<>2 THEN 3360
3240 IF S9=2 THEN 3300
3250 RMOVE @N0:S1/2,S2/3
3260 RDRAW @N0:-S1/2,-S2
3270 RDRAW @N0:-S1/2,S2
3280 RDRAW @N0:S1,0
3290 GO TO 3360
3300 REM:::::::::: PLOT SQUARES ::::::::::::::

```

```
3310 RMOVE @N0:S1/2,-S2/2
3320 RDRAW @N0:0,S2
3330 RDRAW @N0:-S1,0
3340 RDRAW @N0:0,-S2
3350 RDRAW @N0:S1,0
3360 NEXT I
3370 RETURN
3380 END
3390 REM
3400 PAGE
3405 REM::: SUBR CHOOSE PLOTTING SYMBOL:::
3410 PRINT "CHOOSE AND KEY IN THE APPROPRIATE SYMBOL NO."
3420 PRINT "      1 FOR TRIANGLE"
3430 PRINT "      2 FOR SQUARE"
3432 INPUT S9
3435 PRINT "CHANGE PEN COLOR IF DESIRED AND PRESS RETURN"
3436 INPUT Z$
3550 RETURN
4000 END
```

APPENDIX I: REFRDIR EXAMPLE AND LISTING

The following computational procedure is used by REFRDIR to determine the phase velocities, v_n^\pm , and intercept times, $t_{o,n}^\pm$, for the direct and reversed refraction profiles (+ and - for the direct and reversed profiles, respectively) for four layers ($n=1,2,3,4$) or three interfaces ($n=2,3,4$). The given data are (see Figure 60): 1) the layer velocities, α_n , 2) the interface dips, δ_n , and 3) the layer thicknesses, H_n^\pm . The last layer, $n=4$, is a semi-infinite half space. The top interface $n=1$, is the air/ground interface and it is assumed to be horizontal. The angle between the interfaces of layer n is ψ_n : $\psi_n = \delta_{n+1} - \delta_n$.

The phase velocities and the intercept times for the first interface ($n=1$ or top surface) are $v_1^\pm = \alpha_1$, $t_{o1}^\pm = 0$.

For interface #2, ($n=2$), we compute:

$$\sin \theta_{12} = \alpha_1/\alpha_2; \quad \cos \theta_{12} = (1 - \sin^2 \theta_{12})^{1/2}$$

then

$$v_2^\pm = \alpha_1 / (\sin \theta_{12} \cos \psi_1 \mp \cos \theta_{12} \sin \psi_1)$$

$$t_{o2}^\pm = (2H_1^\pm/\alpha_1) \cos \theta_{12}.$$

For interface #3 ($n=3$), we compute:

$$\sin \theta_{23} = \alpha_2/\alpha_3; \quad \cos \theta_{23} = (1 - \sin^2 \theta_{23})^{1/2}$$

$$\sin \theta_{13}^\pm = (\alpha_1/\alpha_2) (\sin \theta_{23} \cos \psi_2 \pm \cos \theta_{23} \sin \psi_2)$$

$$\cos \theta_{13}^\pm = (1 - \sin^2 \theta_{13}^\pm)^{1/2}$$

then

$$v_3^\pm = \alpha_1 / (\sin \theta_{13}^\pm \cos \psi_1 \mp \cos \theta_{13}^\pm \sin \psi_1)$$

$$t_{o3}^\pm = (2H_2^\pm/\alpha_2) \cos \theta_{23} + (H_1^\pm/\alpha_1) (\cos \theta_{13}^+ + \cos \theta_{13}^-).$$

Finally, for interface #4, we compute:

$$\sin \theta_{34} = \alpha_3/\alpha_4; \quad \cos \theta_{34} = (1 - \sin^2 \theta_{34})^{1/2}$$

$$\sin \theta_{24}^{\pm} = (\alpha_2/\alpha_3) (\sin \theta_{34} \cos \psi_3 \pm \cos \theta_{34} \sin \psi_3)$$

$$\cos \theta_{24}^{\pm} = (1 - \sin^2 \theta_{24}^{\pm})^{1/2}$$

$$\sin \theta_{14}^{\pm} = (\alpha_1/\alpha_2) (\sin \theta_{24}^{\pm} \cos \psi_2 \pm \cos \theta_{24}^{\pm} \sin \psi_2)$$

$$\cos \theta_{14}^{\pm} = (1 - \sin^2 \theta_{14}^{\pm})^{1/2}$$

and then finally,

$$v_4^{\pm} = \alpha_1 / (\sin \theta_{14}^{\pm} \cos \psi_1 \mp \cos \theta_{14}^{\pm} \sin \psi_1)$$

$$t_{o4}^{\pm} = (2H_3^{\pm}/\alpha_3) \cos \theta_{34} + (H_2^{\pm}/\alpha_2) (\cos \theta_{24}^{\pm} + \cos \theta_{24}^{\mp}) \\ + (H_1^{\pm}/\alpha_1) (\cos \theta_{14}^{\pm} + \cos \theta_{14}^{\mp}).$$

Note, the computations of t_{on}^{\pm} are made as a running sum; each term is computed as the values of the $\cos \theta_{in}^{\pm}$ are computed.

The equation relating the layer "thicknesses" of the reversed profile, H_n^- , to those of the direct profile, H_n^+ , is:

$$H_n^- = H_n^+ - L \sin \psi_n \prod_{i=0}^{n-1} \cos \psi_i$$

where the symbol \prod represents a product; that is

$$\prod_{i=0}^2 \cos \psi_i = \cos \psi_0 \cos \psi_1 \cos \psi_2$$

(recall $\psi_0 = 0$ and, therefore, $\cos \psi_0 = 1$).


```

10**FRN**R0SD441/PLOTS,E
20C          REFRAC 1          (A.F. GANGI/W. DILLON)
30C
40C  PROGRAM REFRAC 1 IS A MODELLING PROGRAM WHOSE INPUT DATA ARE:
50C    1). THE NUMBER OF LAYERS . . . . . (NLAYRS)
60C    2). THE VELOCITY IN EACH LAYER . . . (ALPHA(N))
70C    3). THE DIP OF THE LAYER INTERFACES IN DEGREES . .
80C          . . . . . (DELTA(N))
90C  AND 4). THE LAYER THICKNESSES . . . . . (HPLUS(N),HMINUS(N))
100C
110C  NOTE: N VARIES FROM 1 TO NLAYRS (1,LE,N,LE,NLAYRS) FOR
120C  ALPHA(N) AND DELTA(N), BUT 1,LE,N,LE,(NLAYRS-1) FOR HPLUS(N)
130C  AND HMINUS(N).
140C
150C  ***** SEE THE DIAGRAM IN FIGURE 1 *****
160C
170C  ALPHA(1), HPLUS(1) & HMINUS(1) ARE THE VELOCITY & LAYER
180C  THICKNESSES OF THE FIRST LAYER WHILE DELTA(1) IS THE DIP
190C  ANGLE OF ITS TOP SURFACE (THE GROUND SURFACE)
200C
210C  THE PROGRAM COMPUTES AND PRINTS OUT, FOR BOTH DIRECT AND
220C  REVERSED PROFILES:
230C    1). THE HORIZONTAL PHASE VELOCITIES . . (VPLUS(N),VMINUS(N))
240C  AND 2). THE INTERCEPT TIMES . . . . . (TPLUS(N),TMINUS(N))
250C  FOR EACH REFRACTION. (2,LE,N,LE,NLAYRS)
260C
270C  *** DEFINITIONS AND LIST OF VARIABLES ***
280C
290C  ALPNM1 = (ALPHA N MINUS 1) = (N-1)ST LAYER'S VELOCITY WHICH IS
300C  COMPARED WITH THE VELOCITY IN LAYER N, ALPHA(N), TO INSURE
310C  THE VELOCITIES ARE MONOTONICALLY DECREASING.
320C
330C  ALPHA(N) = VELOCITY IN LAYER N. (1,LE,N,LE,NLAYRS)
340C
350C  COSPSI = (COSINE PSI) = COSINE OF THE ANGLE BETWEEN LAYER N'S
360C  INTERFACES, PSI(N). (1,LE,N,LE,NLAYRS-1)
370C
380C  CUSP1 = (COSINE PSI(1)) = COSINE OF THE ANGLE BETWEEN THE
390C  FIRST LAYER'S SURFACES.
400C
410C  CTMIN = (COSINE THETAM(I,N)) = COSINE OF THE ANGLE BETWEEN THE
420C  ITH=INTERFACE NORMAL AND THE RAY WHICH REFRACTS ALONG THE NTH
430C  INTERFACE (N>1). THIS IS FOR UPWARD TRAVELLING WAVES. (SEE
440C  FIGURE 1 AND THETAM(I,N)).
450C
460C  CTPIN = (COSINE THETAP(I,N)) = SAME AS CTMIN EXCEPT FOR THE
470C  DOWNWARD TRAVELLING WAVES.
480C
490C  DELTA(N) = THE DIP ANGLE (IN DEGREES) OF THE NTH INTERFACE, THE
500C  TOP SURFACE OF LAYER N. (DELTA(1) = TOP SURFACE DIP ANGLE =
510C  ZERO DEGREES). (1,LE,N,LE,NLAYRS)
520C
530C  HMINUS(N) = THE THICKNESS OF THE NTH LAYER FOR THE REVERSED
540C  PROFILE (SEE FIGURE 1). (1,LE,N,LE,NLAYRS-1)
550C

```

560C HPLUS(N) = THE SAME AS HMINUS(N) EXCEPT FOR THE DIRECT PROFILE
 570C
 580C NLAYRS = (NUMBER OF LAYERS) = NUMBER OF LAYERS FOR WHICH
 590C VELOCITIES ARE GIVEN, (THE LAST LAYER IS A HALF SPACE)
 600C
 610C NX2LST = NEXT TO LAST) = NLAYRS - 1
 620C
 630C P = 0.0174532925 = PI/180 = CONVERSION FACTOR, DEGREES TO RADIANS
 640C
 650C PSI(N) = ANGLE (IN RADIANS) BETWEEN THE SURFACES OF THE NTH
 660C LAYER = P*(DELTA(N+1) - DELTA(N)), (1,LE,N,LE,NLAYRS-1)
 670C
 680C SINPSI = THE SINE OF PSI(N), (SEE COSPSI, PSI(N))
 690C
 700C SINP1 = (SINE OF PSI(1)), (SEE COSP1)
 710C
 720C STMIN = (SINE THETAM(I,N)) = SINE OF THETA MINUS (SEE CTMIN)
 730C
 740C STPIN = (SINE THETAP(I,N)) = SINE OF THETA PLUS (SEE CTPIN)
 750C
 760C THETAM(I,N) = (THETA MINUS) = ANGLE BETWEEN THE ITH-INTERFACE NUR-
 770C MAL AND THE RAY OF THE WAVE THAT REFRACTS ALONG THE NTH INTER-
 780C FACE (N>1), THIS IS FOR UPWARD TRAVELLING RAYS, (SEE FIG. 1)
 790C
 800C THETAP(I,N) = (THETA PLUS) = SAME AS THETAM EXCEPT THIS IS FOR
 810C DOWNWARD TRAVELLING RAYS, (SEE FIGURE 1)
 820C
 830C TMINUS(N) = INTERCEPT TIME FOR THE WAVE REFRACTED FROM THE NTH
 840C INTERFACE FOR THE REVERSED PROFILE, (2,LE,N,LE,NLAYRS)
 850C
 860C TPLUS(N) = INTERCEPT TIME FOR THE WAVE REFRACTED FROM THE NTH
 870C INTERFACE FOR THE DIRECT PROFILE, (2,LE,N,LE,NLAYRS)
 880C
 890C TMINUN = THE RUNNING SUM FOR TMINUS(N)
 900C
 910C TPLUSN = THE RUNNING SUM FOR TPLUS(N)
 920C
 930C VMINUS(N) = HORIZONTAL PHASE VELOCITY OF THE REFRACTION FROM
 940C THE NTH LAYER FOR THE REVERSED PROFILE, (2,LE,N,LE,NLAYRS)
 950C
 960C VPLUS(N) = HORIZONTAL PHASE VELOCITY OF THE REFRACTION FROM
 970C THE NTH LAYER FOR THE DIRECT PROFILE, (2,LE,N,LE,NLAYRS)
 980C
 990C VRATIO = ALPHA(I)/ALPHA(I+1) = VELOCITY RATIO
 1000C
 1010C ***** EQUATIONS USED BY REFRAC 1 *****
 1020C
 1030C 1. SIN(THETA(N-1,N) = ALPHA(N-1)/ALPHA(N)
 1040C
 1050C 2. SIN(THETAP(I-1,N) = (ALPHA(I-1)/ALPHA(I)) *
 1060C (SIN(THETAP(I,N) + PSI(I))
 1070C
 1080C 3. SIN(THETAM(I-1,N) = (ALPHA(I-1)/ALPHA(I)) *
 1090C (SIN(THETAM(I,N) - PSI(I))
 1100C

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1110C 4. VMINUS(N) = ALPHA(1)/SIN(THETAP(1,N) + PSI(1))
1120C
1130C 5. VPLUS(N) = ALPHA(1)/SIN(THETAM(1,N) - PSI(1))
1140C
1150C 6. TPLUS(0,N) = SUM (OVER I=1 TO I=N-1) OF
1160C     HPLUS(I)*(COS(THETAP(I,N)) + COS(THETAM(I,N)))/ALPHA(I)
1170C
1180C 7. TMINUS(0,N) = SUM (OVER I=1 TO I=N-1) OF
1190C     HMINUS(I)*(COS(THETAP(I,N)) + COS(THETAM(I,N)))/ALPHA(I)
1200C
1210C
1220C *****
1230C
1240C     *** BEGIN PROGRAM REFRAC 1 ***
1250C
1260C
1270     P=0.0174532925
1280C DIMENSION INPUT DATA ARRAYS AND COMPUTED ARRAY
1290     REAL ALPHA(50),ALPA(50),DELTA(50),HPLUS(50),HMINUS(50), PSI(50)
1300C
1310C DIMENSION AND INITIALIZE OUTPUT DATA ARRAYS
1320     REAL TPLUS(50),TMINUS(50),VPLUS(50),VMINUS(50)
1330     DATA TPLUS,TMINUS,VPLUS,VMINUS/200*0,0/
1340     REAL X(50),Y(50),SPRDLN,SUMCOS,SIGH
1350     INTEGER D
1360C
1370C READ INPUT DATA: NUMBER OF LAYERS (NLAYRS), LAYER VELOCITIES (AL=
1380C PHA), DIP ANGLES (DELTA) AND LAYER THICKNESSES(HPLUS)
1390     PRINT 7000
1400 7000 FORMAT(1H1,4X,"INPUT NUMBER OF LAYERS IN MODEL",/)
1410     READ 1000,NLAYRS
1420 1000 FORMAT(V)
1430C
1440     PRINT 7200
1450 7200 FORMAT(1H1,4X,"INPUT LENGTH OF SHOT SPREAD",/)
1460     READ 1000,SPRDLN
1470     PRINT 7100
1480 7100 FORMAT(1H1,4X,"FOR EACH LAYER INPUT A LINE ENTRY WITH THE
1490 & FOLLOWING DATA",/,4X,"SEPARATED BY COMMAS: LAYER VELOCITY,
1500 &DIP OF INTERFACE",/,4X,"LAYER THICKNESS",/)
1510     ALPNM1=0.
1520     DO 10 N=1,NLAYRS
1530     READ 1000,ALPHA(N),DELTA(N),HPLUS(N)
1540     ALPA(N)=ALPHA(N)
1550     ALPHA(N)=ALPHA(N)/1000
1560C
1570C THE FOLLOWING CHECKS FOR MONOTONICALLY INCREASING VELOCI-
1580C TIES, IF THEY DECREASE, PROGRAM PRINTS ERROR MESSAGE & STOPS,
1590C
1600     IF (ALPHA(N).LT.ALPNM1) GOTO 900
1610     ALPNM1 = ALPHA(N)
1620 10 CONTINUE
1630     DO 12 N=1,NLAYRS=1
1635     L=N
1640     CALL CHMINUS(HPLUS,SPRDLN,L,P,DELTA,HMINUS)

```

```

1650 12 CONTINUE
1660C
1670C PRINT OUT THE DATA READ IN ABOVE TO CHECK FOR ACCURACY
1680 PRINT 9000,NLAYRS
1690 9000 FORMAT(1H1,4X,'VELOCITIES ARE IN METERS/SEC',
1700 & ' (OR FT/SEC), TIMES ARE IN',/,
1710 & 5X,'MILLISECS AND LAYER THICKNESSES ARE IN METERS,(FT)',//,
1720 & 5X,'THERE ARE ',I2,' LAYERS IN THIS MODEL',//,
1730 & 5X,'LAYER NO. VELOCITY DIP (DEGREES) H+',4X,'H=')
1740C
1750 NX2LST=NLAYRS-1
1760C
1770 DO 20 N=1,NX2LST
1780 PRINT 9100,N,ALPHA(N),DELTA(N),HPLUS(N),HMINUS(N)
1790 9100 FORMAT (1H0,7X,I2,6X,F7.0,3X,5F11.1)
1800C CALCULATE AND CONVERT LAYER ANGLES, PSI (IN RADIANS), FROM THE
1810C DIP ANGLES, DELTA (IN DEGREES)
1820 PSI(N) = P*(DELTA(N+1) - DELTA(N))
1830 20 CONTINUE
1840 PRINT 9200,NLAYRS,ALPHA(NLAYRS),DELTA(NLAYRS)
1850 9200 FORMAT (1H0,7X,I2,6X,F7.0,3X,F11.1)
1860C
1870C DO LOOP 50 PERFORMS THE COMPUTATION OF TPLUS(N), TMINUS(N),
1880C VPLUS(N) & VMINUS(N) (2,LE,N,LE,NLAYRS), TPLUS(1)=TMINUS(1)=0.0,
1890C AND VPLUS(1) = VMINUS(1) = ALPHA(1).
1900C
1910 SINP1 = SIN(PSI(1))
1920 COSP1 = SQRT(1.0 - SINP1*SINP1)
1930 DO 50 N=2,NLAYRS
1940C
1950C THE COMPUTATION IS STARTED BY FINDING SIN(THETA(N=1,N)) (OR
1960C STPIN) USING EQUATION 1. THE COSINE (CTPIN) IS COMPUTED FROM
1970C THE SINE. STPIN & CTPIN ARE SET EQUAL TO STMIN & CTMIN, RES-
1980C PECTIVELY, BECAUSE THETAP(N=1,N) = THETAM(N=1,N).
1990 STPIN = ALPHA(N-1)/ALPHA(N)
2000 CTPIN = SQRT(1.0 - STPIN*STPIN)
2010 STMIN = STPIN
2020 CTMIN = CTPIN
2030C
2040C THE RUNNING SUMS FOR TPLUS AND TMINUS ARE INITIALIZED TO THE
2050C LAST TERMS IN EQUATIONS 6 & 7.
2060C
2070 TEMP = 2.0*CTPIN/ALPHA(N-1)
2080 TPLUSN = HPLUS(N-1)*TEMP
2090 TMINUN = HMINUS(N-1)*TEMP
2100C
2110C IF N=2 (CORRESPONDING TO THE FIRST REFRACTED WAVE FROM THE
2120C SECOND INTERFACE), THE SUMS FOR TPLUS & TMINUS HAVE JUST THE
2130C ABOVE TERMS AND THE PROGRAM JUMPS TO LINE 40 TO COMPUTE
2140C VPLUS AND VMINUS.
2150C
2160 IF (N.EQ.2) GOTO 40
2170C
2180C DO LOOP 30 COMPUTES THE REMAINING TERMS OF TPLUS & TMINUS (THE
2190C SUMS IN EQUATIONS 6 & 7).

```

```

2200C
2210      DO 30 M=3,N
2220          I = N-M+1
2230          PSI1 = PSI(I+1)
2240          SINPSI = SIN(PSI1)
2250          COSPSI = SQRT(1.0 - SINPSI*SINPSI)
2260          VRATIO = ALPHA(I)/ALPHA(I+1)
2270C
2280C      IN COMPUTING TPLUS & TMINUS, THE SINES AND COSINES OF THE
2290C      THETAS FROM THETA(N=1,N) TO THETA(1,N) ARE NEEDED. THESE ARE
2300C      COMPUTED USING EQUATIONS 2 & 3.
2310C
2320          STPIN = VRATIO*(STPIN*COSPSI + CTPIN*SINPSI)
2330          STMIN = VRATIO*(STMIN*COSPSI - CTMIN*SINPSI)
2340          CTPIN = SQRT(1.0 - STPIN*STPIN)
2350          CTMIN = SQRT(1.0 - STMIN*STMIN)
2360          TEMP = (CTPIN + CTMIN)/ALPHA(I)
2370          TPLUSN = TPLUSN + HPLUS(I)*TEMP
2380          TMINUN = TMINUN + HMINUS(I)*TEMP
2390      30  CONTINUE
2400C
2410C      UPON EXITING DO LOOP 30, TPLUS(N) & TMINUS(N) HAVE BEEN COM-
2420C      PUTED. STPIN IS THE SIN OF THETAP(1,N), CTPIN IS ITS COSINE,
2430C      AND STMIN & CTMIN ARE THEIR COUNTERPARTS FOR THE REVERSED PRO-
2440C      FILE. THEN VPLUS(N) & VMINUS(N) ARE COMPUTED USING EQUATIONS
2450C      4 AND 5, RESPECTIVELY.
2460C
2470      40  TPLUS(N) = TPLUSN
2480          TMINUS(N) = TMINUN
2490C
2500          VMINUS(N) = ALPHA(1)/(STPIN*COSPI + CTPIN*SINPI)
2510          VPLUS(N) = ALPHA(1)/(STMIN*COSPI - CTMIN*SINPI)
2520      50  CONTINUE
2530C
2540C      **** PRINT THE RESULTS OF THE PROGRAM ****
2550C
2560      PRINT 9300
2570 9300  FORMAT (1H0,/,16X,'***** CALCULATED RESULTS *****',/,
2580      &      5X,'THE HORIZONTAL PHASE VELOCITIES AND THE ',
2590      &      'INTERCEPT TIMES',/,
2600      &      5X,'FOR THE DIRECT (+) AND REVERSED (-) PROFILES',/,
2610      &      4X,'INTERFACE NO. PHASE VEL+ PHASE VEL-',8X,'T+',9X,'T=')
2620C
2630      DO 60 N=2,NLAYRS
2640          VPLUS(N)=VPLUS(N)*1000
2650          VMINUS(N)=VMINUS(N)*1000
2660          PRINT 9400,N,VPLUS(N),VMINUS(N),TPLUS(N),TMINUS(N)
2670          VPLUS(N)=VPLUS(N)/1000
2680          VMINUS(N)=VMINUS(N)/1000
2690 9400  FORMAT (1H0,7X,I2,3X,2F15,3,3X,2F11,1)
2700      60  CONTINUE
2710          GOTU 999
2720C
2730      900 PRINT 9900
2740 9900  FORMAT (1H1,9X,'CHECK YOUR INPUT VELOCITIES ',/,

```

```

2750      K      5X, 'THEY ARE NOT MONOTONICALLY INCREASING,')
2760      GO TO 3000
2770C
2780 999  CONTINUE
2790C ****PLOT REFRACTION PROFILE LINES(T/D PLOT) *****
2800C ****PLOT DIRECT PROFILE LINE *****
2810 2605 PRINT 7240
2820 7240 FORMAT(1H1,4X, 'INPUT 1 IF YOU WISH TO PLOT FORWARD',/,
2830      84X, 'PROFILE LINE ONLY',/,4X, 'ENTER 2 TO PLOT FORWARD AND REVERSE
2840      &PROFILE')
2850      READ 1000,M
2860      Y(1)=0
2870      X(1)=0
2880      X(2)=TPLUS(2)/(1/ALPHA(1)-1/VPLUS(2))
2890      Y(2)=(1/ALPHA(1))*X(2)
2900      K=3
2910      DO 70 N=2,NLAYRS=1
2920          X(K)=(TPLUS(N+1)-TPLUS(N))/(1/VPLUS(N)-1/VPLUS(N+1))
2930          Y(K)=TPLUS(N)+(1/VPLUS(N))*X(K)
2940      INTEGER D
2950          K=K+1
2960 70  CONTINUE
2970      X(K)=SPRDLN
2980      Y(K)=TPLUS(NLAYRS)+(1/VPLUS(NLAYRS))*X(K)
2990      IF(M.EQ.1) GO TO 2900
3000C****PLOT REVERSE PROFILE LINE ****
3010      K=K+1
3020      X(K)=SPRDLN
3030      Y(K)=0
3040      K=K+1
3050      X(K)=TMINUS(2)/(1/ALPHA(1)-1/VMINUS(2))
3060      Y(K)=(1/ALPHA(1))*X(K)
3070      X(K)=SPRDLN-X(K)
3080      K=K+1
3090      DO 80 N=2,NLAYRS=1
3100          X(K)=(TMINUS(N+1)-TMINUS(N))/(1/VMINUS(N)-1/VMINUS(N+1))
3110          Y(K)=TMINUS(N)+(1/VMINUS(N))*X(K)
3120      X(K)=SPRDLN-X(K)
3130      K=K+1
3140 80  CONTINUE
3150      X(K)=SPRDLN
3160      Y(K)=TMINUS(NLAYRS)+(1/VMINUS(NLAYRS))*X(K)
3170      X(K)=0
3180 2900  YMAX=Y(1)
3190      DO 89 KK=2,K
3200      YMAX=MAX(YMAX,Y(KK))
3210 89  CONTINUE
3220      PRINT 8500,YMAX
3230 8500  FORMAT(1H1,4X, 'LARGEST VALUE OF Y FOR SCALING IS:',2X,F6.1)
3240      CALL PLOT2(X,Y,K)
3250 3000  STOP
3260      END
3270      SUBROUTINE CHMINUS(HPLUS,SPRDLN,N,P,DELTA,HMINUS)
3280      DIMENSION HPLUS(10),DELTA(10),HMINUS(10)
3290      INTEGER D

```

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14149140 05/26/82

FILE PAGE NO. 7

```
3300      SUMCOS=1.0
3310      DO 93 D=1,N=1
3320      SIGH=DELTA(D+1)=DELTA(D)
3330      SUMCOS=SUMCOS*COS(SIGH*P)
3340 93    CONTINUE
3350      SIGH=DELTA(N+1)=DELTA(N)
3360      HMINUS(N)=HPLUS(N)=SPRDLN*SIN(SIGH*P)*SUMCOS
3370      RETURN
3380      END
```

APPENDIX J: REFRINV EXAMPLE AND LISTING

The following procedure is used by REFRINV to determine: 1) the layer velocities, α_n , 2) the layer "thicknesses", H_n^{\pm} , and the interface dip angles, δ_n , for layers with plane dipping interfaces all having the same strike. The given or input data are: 1) the intercept time, T_{on}^{\pm} , and 2) the horizontal phase velocities, V_n^{\pm} , for direct and reversed refraction profiles. All arrival times are assumed to be measured on the surface and the + and - signs refer to the quantities associated with the direct and the reversed profiles, respectively.

The velocity in the top layer, α_1 , is given because it is the horizontal phase velocity of the direct p wave (and has the same value for both the direct and the reversed profiles). The intercept times of the direct waves, T_{01}^{\pm} , for these profiles are both zero and the dip angle of the top surface (the $n=1$ "interface"), δ_1 , is defined to the zero.

The computation, therefore, is started with the data from the second interface (i.e., the first refraction) corresponding to $n=2$ and proceeds as follows:

Compute

$$\begin{aligned} \text{ANGMNP},M &= \theta_{12} + \psi_1 = \arcsin(\alpha / V_2^{\pm}) \\ &= \text{ANGNNP},M \end{aligned}$$

and obtain

$$\alpha_1 / \alpha_2 = \sin \theta_{12} = \sin .5 (\text{ANGNNP} + \text{ANGNNM})$$

$$\alpha_2 = \alpha_1 / \sin \theta_{12}$$

$$\psi_1 = .5 (\text{ANGNNP} - \text{ANGNNM})$$

$$\text{TEMP2} = \alpha_1 / (2 \cos \theta_{12})$$

$$H_1^{\pm} = T_{02}^{\pm} \text{TEMP2}$$

thus, we have computed α_2 , ψ_1 (or δ_2) and H_1^\pm .

Then, for $n=3$, we compute

$$\text{ANGMNP},M = \theta_{13}^\pm \pm \psi_1 = \arcsin(\alpha_1/V_3^\pm)$$

and we enter DO-loop 30, to compute

$$\text{THETAP},M = \theta_{13}^\pm = \text{ANGMNP},M \mp \psi_1$$

$$\text{ANGMNP},M = \theta_{23} \pm \psi_2 = \arcsin(\alpha_2 \sin \theta_{13}^\pm / \alpha_1)$$

$$\text{TEMP1} = (\cos \theta_{13}^+ + \cos \theta_{13}^-) / \alpha_1$$

$$\text{TPLUSN}, \text{TMINSN} = T_{03}^\pm - H_1^\pm \text{TEMP1}.$$

We then exit DO-loop 30 and compute

$$\text{ANGNNP},M = \text{ANGMNP},M$$

$$\alpha_3 / \alpha_2 = \sin \theta_{23} = \sin .5(\text{ANGNNP} + \text{ANGNNM})$$

$$\alpha_3 = \alpha_2 / \sin \theta_{23}$$

$$\psi_2 = .5(\text{ANGNNP} - \text{ANGNNM})$$

$$\text{TEMP2} = \alpha_2 / (2 \cos \theta_{23})$$

$$H_2^\pm = (T_{03}^\pm - H_1^\pm \text{TEMP1}) \text{TEMP2}$$

Thus, we have computed α_3 , ψ_2 (or $\delta_3 = \delta_2 + \psi_2$) and H_2^\pm as well as the previous values of α_2 , ψ_1 , and H_1^\pm by using the data from the first two refractions, that is, the refractions along interfaces $n=2$ and $n=3$. (See Figure 1).

For $n=4$, we use the above results and the data from the refractions along the $n=4$ interface (V_4^\pm and T_{04}^\pm) as follows: we compute

$$\text{ANGMNP},M = \theta_{14}^\pm \pm \psi_1 = \arcsin(\alpha_1/V_4^\pm)$$

and then enter DO-loop 30 to compute

$$\text{THETAP},M = \theta_{14}^\pm = \text{ANGMNP},M \mp \psi_1$$

$$\text{ANGMNP},M = \theta_{24} \pm \psi_2 = \arcsin(\alpha_2 \sin \theta_{14}^\pm / \alpha_1)$$

$$\text{TEMP1} = (\cos \theta_{14}^+ + \cos \theta_{14}^-) / \alpha_1$$

$$\text{TPLUSN}, \text{TMINSN} = T_{03}^\pm - H_1^\pm \text{TEMP1}$$

$$\text{THETAP},M = \theta_{24}^\pm = \text{ANGMNP},M \mp \psi_2$$

$$\text{ANGMNP},M = \theta_{34} \pm \psi_3 = \arcsin(\alpha_3 \sin \theta_{24}^\pm / \alpha_2)$$

$$\text{TEMP1} = (\cos \theta_{24}^+ + \cos \theta_{24}^-) / \alpha_2$$

$$\text{TPLUSN}, \text{TMINSN} = \text{TPLVS}, \text{TMINSN} - H_2^+ \text{TEMP1}.$$

We then exit DO-loop 30 and compute

$$\text{ANGNNP}, \text{M} = \text{ANGMNP}, \text{M}$$

$$\alpha_4 / \alpha_3 = \sin \theta_{34} = \sin .5 (\text{ANGNNP} + \text{ANGNNM})$$

$$\alpha_4 = \alpha_3 / \sin \theta_{34}$$

$$\psi_3 = .5 (\text{ANGNNP} - \text{ANGNNM})$$

$$\text{TEMP2} = \alpha_3 / (2 \cos \theta_{34})$$

$$H_3^+ = (\text{TPLUSN}, \text{TMINSN}) \text{TEMP2}.$$

Thus, we have computed α_4 , ψ_3 (or $\delta_4 = \delta_3 + \psi_3$) and H_3^+ . We now have all the parameters for a four-layer model (three layers over a half space).

The data are tabulated with all the data for a particular layer on one line in the following order: 1) the layer number, 2) the layer velocity, 3) the dip of the top interface, 4) the layer "thickness" for the direct profile and 5) the layer "thickness" for the reversed profile.

10C REFRAC 2 IS AN INVERSE PROGRAM. IT DETERMINES MODEL PARAMETERS
20C FROM MEASURED VALUES.

30C

40C PROGRAM REFRAC 2 HAS FOR ITS INPUT:
50C (FROM DIRECT AND REVERSED PROFILES)

- 60C 1) HORIZONTAL PHASE VELOCITIES AND
70C 2) INTERCEPT TIMES FOR EACH REFRACTION AND
80C 3) THE VELOCITY IN THE FIRST LAYER.

90C

100C REFRAC 2 COMPUTES AS OUTPUT:

- 110C 1) THE VELOCITY IN EACH LAYER,
120C 2) THE DIP (IN DEGREES) OF EACH LAYER INTERFACE AND
130C 3) THE LAYER THICKNESSES FOR THE DIRECT AND REVERSED
140C PROFILES.

150C

160C PROGRAM REFRAC 2 IS THE INVERSE OF THE MODELLING PROGRAM
170C REFRAC 1.

180C

190C

200C

*** LIST OF VARIABLES AND THEIR MEANINGS ***

210C

220C ALPHA(N) = THE VELOCITY (OR WAVE SPEED) IN THE NTH LAYER

230C

240C ANGMNM = (ANGLE(M,N)MINUS) = THETAM(M,N) - PSI(M) =
250C = ARSIN(SIN(THETAM)/SPEEDR(M)) (SEE EQN'S 1B, 2B & 3B)

260C

270C ANGMNP = (ANGLE(M,N)PLUS) = THETAP(M,N) + PSI(M) =
280C = ARSIN(SIN(THETAP)/SPEEDR(M)) (SEE EQN'S 1A, 2A & 3A)

290C

300C ANGNNM = (ANGLE(N=1,N)MINUS) = THETA(N=1,N) - PSI(N=1) =
310C = ARSIN(SIN(THETAM)/SPEEDR(N=1)) (SEE EQUATION 3B)

320C

330C ANGNNP = (ANGLE(N=1,N)PLUS) = THETA(N=1,N) + PSI(N=1) =
340C = ARSIN(SIN(THETAP)/SPEEDR(N=1)) (SEE EQUATION 3A)

350C

360C C = CONVERSION FACTOR, RADIANS TO DEGREES = 57.29578

370C

380C DELTN = THE DIP ANGLE OF THE NTH INTERFACE

390C

400C HMINUS(N) = THE LAYER "THICKNESS" FOR THE NTH LAYER, REVERSED
410C PROFILE, (SEE FIGURE 1)

420C

430C HPLUS(N) = THE LAYER "THICKNESS" FOR THE NTH LAYER, DIRECT
440C PROFILE, (SEE FIGURE 1)

450C

460C NLAYS = (NUMBER OF LAYERS) = THE NUMBER OF LAYERS FOR WHICH
470C VELOCITIES WILL BE CALCULATED

480C

490C NM1 = (N MINUS 1) = N-1

500C

510C NX2LST = (NEXT TO LAST) = THE NUMBER OF THE NEXT-TO-LAST LAYER

520C

530C PSI(N) = THE ANGLE BETWEEN THE SURFACES OF THE NTH LAYER

540C

550C SPEEDR(N) = (SPEED RATIO) = SPEDRN = THE VELOCITY IN THE

560C (N=1)ST LAYER DIVIDED BY THE VELOCITY IN THE NTH LAYER

570C

580C THETAM = (THETA MINUS) = THETAM(1,N) = THE ANGLE BETWEEN THE
590C ITH=INTERFACE NORMAL AND THE RAY OF THE WAVE THAT REFRACTS
600C ALONG THE NTH INTERFACE (N>1). THIS IS FOR A DOWNWARD=
610C TRAVELLING WAVE. (SEE FIGURE 1)

620C

630C THETAP = (THETA PLUS) = THETAP(1,N) = SAME AS THETAM EXCEPT
640C THIS IS FOR AN UPWARD=TRAVELLING WAVE. (SEE FIGURE 1)

650C

660C TMINUS(N) = THE INTERCEPT TIME FOR THE NTH REFRACTION (FOR
670C THE REVERSED PROFILE)

680C

690C TMINSN = THE RUNNING (DECREMENTING) SUM OF THE INTERCEPT TIME;
700C USED TO COMPUTE HMINUS (SEE EQUATION 9) FOR THE REVERSED
710C PROFILE.

720C

730C TPLUS(N) = SAME AS TMINUS(N), EXCEPT FOR THE DIRECT PROFILE

740C

750C TPLUSN = SAME AS TMINSN, EXCEPT FOR THE DIRECT PROFILE

760C

770C VMINUS(N) = (VELOCITY MINUS) = HORIZONTAL PHASE VELOCITY FOR
780C THE REVERSED PROFILE DUE TO A REFRACTION ON THE NTH
790C INTERFACE.

800C

810C VPLUS(N) = (VELOCITY PLUS) = HORIZONTAL PHASE VELOCITY FOR
820C THE DIRECT PROFILE DUE TO A REFRACTION ON THE NTH
830C INTERFACE.

840C

850C V1 = THE VELOCITY IN THE FIRST LAYER

860C

870C

880C ***** EQUATIONS USED *****

890C

900C THETAP(1,N) + PSI(1) = ARSIN(ALPHA(1)/VMINUS(N))
910C = ANGMNP (M=1) (1A)

920C

930C THETAM(1,N) - PSI(1) = ARSIN(ALPHA(1)/VPLUS(N))
940C = ANGMMN (M=1) (1B)

950C

960C THETAP(M,N) + PSI(M) = ARSIN(SIN(THETAP(M=1,N))/SPEEDR(M))
970C = ANGMNP (2A)

980C

990C THETAM(M,N) - PSI(M) = ARSIN(SIN(THETAM(M=1,N))/SPEEDR(M))
1000C = ANGMMN (2B)

1010C

1020C THETA(N=1,N) + PSI(N=1) = ARSIN(SIN(THETAP(N=2,N))/SPEEDR(N=1))
1030C = ANGNNP (M=N=1) (3A)

1040C

1050C THETA(N=1,N) - PSI(N=1) = ARSIN(SIN(THETAM(N=2,N))/SPEEDR(N=1))
1060C = ANGNNM (M=N=1) (3B)

1070C

1080C ALPHA(N=1)/ALPHA(N) = SIN(THETA(N=1,N)) = SIN(.5*(ANGNNP+ANGNNM))
1090C = SPEEDR(N) = SPEEDRN (4)

1100C

```

1110C PSI(N=1) = 0,5*(ANGNNP = ANGNM) (5)
1120C
1130C TEMP1 = (COS(THETAP) + COS(THETAM))/ALPHA(M=1) (6)
1140C
1150C TEMP2 = 0,5*ALPHA(N=1)/SQRT(1, = SPEEDR**2) (7)
1160C
1170C HPLUS(N=1) = TEMP2*(TPLUS(N) = SUM FROM I=1 TO N=2 OF
1180C HPLUS(I)*TEMP1) (8)
1190C
1200C HMINUS(N=1) = TEMP2*(TMINUS(N) = SUM FROM I=1 TO N=2 OF
1210C HMINUS(I)*TEMP1) (9)
1220C
1230C
1240C *****
1250C ***** START PROGRAM REFRAC 2 *****
1260C *****
1270C
1280C *** INPUT
1290 REAL VPLUS(50),VMINUS(50),TPLUS(50),TMINUS(50)
1300C
1310C *** OUTPUT
1320 REAL ALPHA(50),HPLUS(50),HMINUS(50),DELTA
1330C
1340C *** VARIABLES
1350 REAL SPEEDR(50),PSI(50)
1360C
1370C ***** READ MODULE *****
1380C
1390 READ 1000,NLAYRS,V1
1400 1000 FORMAT(V)
1410C DECIMAL POINT IN COLUMN 11
1420 ALPHA(1)=V1
1430 NX2LST=NLAYRS-1
1440C
1450 DO 10 N=2,NLAYRS
1460 READ 1000,VPLUS(N),VMINUS(N),TPLUS(N),TMINUS(N)
1480C DECIMAL POINTS IN COLUMNS 3,11,21 AND 29
1490 10 CONTINUE
1500C
1510C ***** PRINT MODULE *****
1520C
1530 PRINT 9000,NX2LST,V1
1540 9000 FORMAT (1H1,4X,"VELOCITIES ARE IN METERS/MILLISEC, ",
1550 & "TIMES ARE IN MILLISEC",/,
1560 & 5X,"AND LAYER THICKNESSES IN METERS",//,
1570 & 5X,"NO. OF REFRACTIONS = ",I2,"; FIRST=LAYER ",
1580 & "VELOCITY IS:",F7,3,///,
1590 & 5X,"INPUT DATA: PHASE VELOCITIES AND ",
1600 & "INTERCEPTS OF REFRACTIONS",/,
1610 & 5X,"MEASURED ON DIRECT (+) AND REVERSED (-) PROFILES",//,
1620 & 4X,"INTERFACE NO. PHASE VEL+ PHASE VEL- T+",
1630 & 9X,"T=")
1640C
1650 DO 15 N=2,NLAYRS
1660 PRINT 9100,N,VPLUS(N),VMINUS(N),TPLUS(N),TMINUS(N)

```

```

1670 9100          FORMAT (1H0,19,4X,2F13.5,2F11.1)
1680 15          CONTINUE
1690C
1700C
1710C          ***** COMPUTATION MODULE *****
1720C
1730C  ALL CALCULATIONS ARE PERFORMED IN DO=LOOP 40
1740C
1750          DO 40 N=2,NLAYRS
1760C
1770C  USE EQUATIONS 1A & 1B TO FIND ANGMNP & ANGMNM (M=1)
1780          ANGMNP = ARSIN(V1/VMINUS(N))
1790          ANGMNM = ARSIN(V1/VPLUS(N))
1800C
1810          TPLUSN = TPLUS(N)
1820          TMINSN = TMINUS(N)
1830          NM1 = N-1
1840C  IF THE FIRST LAYER'S PARAMETERS ARE BEING COMPUTED,
1850C          SKIP DO=LOOP 30 (GOTO 35)
1860          IF (N, EQ, 2) GOTO 35
1870C
1880C  DO=LOOP 30 COMPUTES THE SUMS IN EQUATIONS 8, AND 9.
1890C
1900          DO 30 M=2,NM1
1910C
1920C  USE EQUATIONS 2A & 2B TO FIND THETAP & THETAM
1930          THETAP = ANGMNP + PSI(M-1)
1940          THETAM = ANGMNM + PSI(M-1)
1950C  USE EQUATIONS 2A & 2B TO FIND NEW ANGMNP & ANGMNM
1960          ANGMNP = ARSIN(SIN(THETAP)/SPEEDR(M))
1970          ANGMNM = ARSIN(SIN(THETAM)/SPEEDR(M))
1980C
1990          TEMP1 = (COS(THETAP) + COS(THETAM))/ALPHA(M-1)
2000          TPLUSN = TPLUSN + HPLUS(M-1)*TEMP1
2010          TMINSN = TMINSN + HMINUS(M-1)*TEMP1
2020 30          CONTINUE
2030C
2040C  UPON EXITING DO=LOOP 30, ANGMNP & ANGMNM ARE (SEE EQNS 3A & 3B)
2050C          THETA(N-1,N) +/- PSI(N-1), RESPECTIVELY
2060C          (THAT IS, ANGNP & ANGNM, RESPECTIVELY)
2070C
2080 35          ANGNP = ANGMNP
2090          ANGNM = ANGMNM
2100C
2110C  USE EQN 4, FIND SPEEDR(N) = ALPHA(N-1)/ALPHA(N), THEN ALPHA(N)
2120          SPEDRN = SIN(0.5*(ANGNP + ANGNM))
2130          SPEEDR(N) = SPEDRN
2140          ALPHA(N) = ALPHA(NM1)/SPEDRN
2150C
2160C  USE EQUATION 5 TO FIND PSI(N-1)
2170          PSI(NM1) = 0.5*(ANGNP - ANGNM)
2180C
2190C  USE EQUATIONS 6 & 9 TO FIND HPLUS(N-1) & HMINUS(N-1)
2200          TEMP2 = ALPHA(NM1)/(2.*SQRT(1. - SPEEDR*SPEDRN))
2210          HPLUS(NM1) = TPLUSN*TEMP2

```

```
2220      HMINUS(NM1) = TMINSN*TEMP2
2230      40 CONTINUE
2240C
2250C      ***** OUTPUT PRINT MODULE *****
2260C
2270      PRINT 9500
2280 9500      FORMAT (1H0,/,16X,***** CALCULATED RESULTS *****,/,
2290      &      5X,"THE WAVE VELOCITIES, INTERFACE DIPS AND ",
2300      &      "LAYER THICKNESSES",/,
2310      &      6X,"LAYER NO. VELOCITY DIP (DEG) H+P,8X,"H=P")
2320C
2330      DELTN = 0.0
2340      C = 57.29578
2350C
2360      DO 50 N=1,NX2LST
2370          PRINT 9600,N,ALPHA(N),DELTN,HPLUS(N),HMINUS(N)
2380 9600      FORMAT (I10,9X,F6.3,3F10.1)
2390C      CALCULATE DELTN; CONVERT ANGLES FROM RADIANS TO DEGREES
2400          DELTN = C*PSI(N) + DELTN
2410      50 CONTINUE
2420C
2430      PRINT 9700,NLAYRS,ALPHA(NLAYRS),DELTN
2440 9700      FORMAT (I10,9X,F6.3,F10.1,////)
2450      STOP
2460      END
```

APPENDIX K: CROSSHOLE LISTING

CROSS

10:24: 4 05/28/82

FILE PAGE NO. 1

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10      CALL FPARAM(1,80)
20C     THIS PROGRAM WAS WRITTEN BY GEORGE H. SKUGLAND AND CHECKED
30C***** CROSSHOLE SEISMIC INTERPRETATION *****
40C     AND MODIFIED BY DRAIN K. BUTLER (1977) TO HELP
50C     DEVELOP A PLAUSIBLE TRUE VELOCITY INTERPRETATION FROM THE APPARENT
60C     VELOCITY PROFILE MEASURED IN THE FIELD BY CROSSHOLE SEISMIC
70C     TECHNIQUES. TRAVEL PATHS ARE ASSUMED TO BE GOVERNED BY SNELL'S
80C     LAW OF REFRACTION,
90C     FROM THE INTERPRETED TRUE VELOCITY PROFILE, A COMPUTED
100C    APPARENT VELOCITY PROFILE IS DERIVED FOR COMPARISON WITH THE
110C    FIELD MEASURED DATA. IN ADDITION, AN OPTION IS AVAILABLE TO
120C    INPUT ANY TRUE VELOCITY PROFILE FROM WHICH AN APPARENT VELOCITY
130C    PROFILE CAN BE CONSTRUCTED AS A FUNCTION OF A SPECIFIED HOLE
140C    SPACING AND DEPTH INTERVAL CONFIGURATION.
150
160
170C    USER HINTS (JULY 1977)
180
190C    1. THIS PROGRAM CAN BE USED FOR SHEAR WAVE AS WELL AS COMPRESSION
200C    WAVE VELOCITIES,
210
220C    2. THE FUNDAMENTAL INTERPRETATION CAPABILITY OF THIS PROGRAM IS
230C    BASED UPON THE MEASUREMENT OF ONE TRUE VELOCITY IN EACH VELOCITY
240C    LAYER. THE WIDEST POSSIBLE HOLE SPACING THAT WILL GIVE ONE
250C    MEASURED TRUE VELOCITY IN EACH VELOCITY LAYER IS PREFERRABLE TO
260C    A CLOSER SPACING, BECAUSE ONLY APPARENT VELOCITIES DEFINITELY
270C    ESTABLISH VELOCITY LAYER INTERFACES. IN GENERAL, THE IDEAL DATA
280C    BASE FOR EACH VELOCITY LAYER WOULD HAVE TWO APPARENT VELOCITIES
290C    RELATIVE TO THE SAME INTERFACE AND ONE TRUE VELOCITY.
300
310C    3. THE INTERPRETATION OF A PROFILE BEGINS AT THE HIGHEST GEOPHONE
320C    AND PROCEEDS DOWNWARD. UNLESS OTHERWISE SPECIFIED, THE FIRST
330C    VELOCITY IS ASSUMED TO BE A TRUE VELOCITY WITH SUCCESSIVE
340C    VELOCITIES THEN SCRUTINIZED FOR INTERPRETATION UNTIL THE NEXT
350C    TRUE VELOCITY IS ENCOUNTERED. IN CONCEPT, THE PROGRAM MOVES DOWN
360C    THE PROFILE FROM TRUE VELOCITY TO TRUE VELOCITY WITH ANY NUMBER OF
370C    APPARENT VELOCITIES (OR NONE AT ALL) IN BETWEEN ADJACENT TRUE
380C    VELOCITIES.
390
400C    4. IF A FIELD MEASURED PROFILE DOES NOT CONTAIN A MEASURED TRUE
410C    VELOCITY IN EACH VELOCITY LAYER, THE OPTION TO INPUT A TRUE
420C    VELOCITY PROFILE CAN GENERATE A COMPUTED APPARENT VELOCITY PROFILE
430C    THAT WILL COINCIDE WITH THE FIELD MEASURED PROFILE IF THE
440C    HYPOTHESIZED TRUE VELOCITY PROFILE IS A VALID POSSIBILITY.
450
460C    5. AN INPUT OPTION IS AVAILABLE TO SPECIFY THE DEEPEST TRUE
470C    VELOCITY. SINCE MOST BOREHOLES END AT A HARDER MATERIAL THAN
480C    ENCOUNTERED ELSEWHERE IN THE PROFILE, THE MINIMUM TIME PATH AT
490C    THE BOTTOM OF THE BOREHOLE PROBABLY GOES DEEPER THAN THE BOREHOLE
500C    DEPTH. THE DEPTH TO THE LAST VELOCITY MAY ALSO BE SPECIFIED IF
510C    A DEPTH GREATER THAN THE DEEPEST GEOPHONE IS DESIRED.
520
530C    6. TRAVEL PATHS ARE ASSUMED TO BEGIN AND END IN THE SAME VELOCITY
540C    LAYER, ALTHOUGH NOT NECESSARILY AT THE SAME DEPTH.
550

```


560C 7. HOLE COORDINATES ARE NORTH POSITIVE, EAST POSITIVE, AND DEPTH.

570

580

590C

FUTURE IMPROVEMENTS

600

610C

1. PROVIDE FOR A TRAVEL PATH TO BEGIN IN ONE LAYER AND END IN THE ADJACENT LAYER. THIS CAPABILITY WILL ALLOW FOR MORE

620C

SOPHISTICATED SOURCE-GEOPHONE AND MULTIPLE GEOPHONE CONFIGURATIONS

630C

640

650C

2. PROVIDE FOR A SPECIFIED INTERFACE SLOPE.

660

670C

3. PROVIDE A MODEL TO GENERATE A MEISSNER WAVE FRONT DIAGRAM

680C

FOR COMPARISON WITH A MEISSNER WAVE FRONT SURVEY TO BE

690C

CONDUCTED IN CONJUNCTION WITH THE CROSSHOLE SURVEY.

700

710C

4. INCORPORATE UPHOLE TIMES TO AID IN THE INTERPRETATION AND TO

720C

PROVIDE VERTICAL WAVE VELOCITIES (IN A SIMILAR MANNER TO THE

730C

U.S. BUREAU OF MINES PROGRAM FOR REFRACTION SEISMIC PROFILING)

740C

FOR CROSSHOLE SURVEYS.

750

760C**** PROGRAM INPUT ****

770

780C

FIRST CARD = FORMAT (12A6)

790C

1-72 DATA IDENTIFICATION

800C

810

820C

SECOND LIST = FORMAT (4I5,4F10,0,2I5)

830C

1-5 INPUT OPTION CODE

840C

1 FOR ARRIVAL TIMES

850C

2 FOR APPARENT VELOCITIES

860C

3 FOR TRUE VELOCITY PROFILE AND ARRIVAL TIMES

870C

4 FOR TRUE VELOCITY PROFILE AND APPARENT VELOCITIES

880C

5 FOR TRUE VELOCITY PROFILE

890C

6-10 STORAGE KEY FOR USE WITH OUTPUT OPTIONS

900C

11-15 OUTPUT OPTION CODE

910C

1 FOR TABDUM=APPARENT VELOCITY AS A FUNCTION OF HOLE S

920C

2 FOR SUMMARY

930C

3 FOR SUMTWO

940C

7 FOR CARRYING OVER THE PREVIOUS TRUE VELOCITY PROFILE

950C

16-17 TYPE OF SUMMARY TABLE DESIRED (FOR USE WITH IUP2=2)

960C

1 FOR PARTIAL SUMMARY THREE HOLE SET

970C

2 FOR FULL SUMMARY THREE HOLE SET

980C

18-20 NUMBER OF SHOT RECORDS PER HOLE SET

990C

31-40 HOLE PAIR AZIMUTH

1000C

21-30 HORIZONTAL DISTANCE BETWEEN BOREHOLES

1010C

41-50 FIRST LAYER TRUE VELOCITY (IF NOT DEFINED BY THE DATA)

1020C

51-60 DEEPEST LAYER TRUE VELOCITY (IF NOT DEFINED BY THE DATA)

1030C

61-65 DEPTH TO THE DEEPEST LAYER (IF KNOWN)

1040C

66-70 NUMBER OF TRUE VELOCITY LAYERS FOR INPLT OPTIONS 3,4,5

1050C

71-75 GEOPHONE SPACING (FOR USE WITH INPUT OPTION 5 ONLY)

1060C

76-80 OUTPUT PUNCH OPTION (FOR USE WITH OPTION 5)

1070

1080C

THIRD LIST = FORMAT (8F10,0)

1090C

1-10 SHOTPOINT DEPTH (Z=COORDINATE)

1100C

11-20 SHOTPOINT LOCAL X=DEVIATION (NORTH DIRECTION POSITIVE)

```

1110C      21=30  SHUTPOINT LOCAL Y=DEVIATION (EAST DIRECTION POSITIVE)
1120C      31=40  GEOPHONE DEPTH (Z=COORDINATE)
1130C      41=50  GEOPHONE LOCAL X=DEVIATION
1140C      51=60  GEOPHONE LOCAL Y=DEVIATION
1150C      61=70  ARRIVAL TIME, SECONDS (FOR USE WITH INPUT OPTION 1 AND 3)
1160C      71=80  APPARENT VELOCITY (FOR USE WITH INPLT OPTION 2 AND 3)
1170      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
1180      &          SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
1190      &          ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
1200      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
1210      & ,VC(20,20)
1220      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
1230      CHARACTER*24 DIN(2)
1235      CHARACTER*60 TITLE
1240      DATA DIN(2)/1H;/
1241      ISTAT=0
1242      GO TO 2
1243 1      CALL DETACH(1,ISTAT,)
1250 2      PRINT 10
1260 10     FORMAT("ENTER THE NAME OF THE DATA FILE YOU WANT TO PROCESS")
1270      READ 820,DIN(1)
1280      IF(DIN(1).EQ.8H          )GO TO 999
1290      CALL ATTACH(1,DIN,3,0,ISTAT,)
1300 820    FORMAT(V)
1310
1320      DATA AFAC / 0.02 /, CFAC / 0.05 /
1330
1340      PRINT 895
1370      READ(1,800) TITLE
1380      READ(1,810)LIN,IOP1,N,IOP2,ISUM,M,DIST,AZIM,VFIRST,VLAST,DLLAST,IMAX,
1390      & DELGS,IPUN
1410      IF(N.EQ.0) N=1
1420      IF(IOP1.EQ.0) GO TO 250
1430
1440      DO 200 I=1,20
1450      DL(I,N)=0.0
1460      VL(I,N)=0.0
1470      SVL(I,N)=0.0
1480 200    K(I,N)=0.0
1490
1500 250    IF(M.GT.JMAX) JMAX=M
1510
1520      IF(IOP1.EQ.0) GO TO 410
1530
1540 400    CALLRINPUT (IOP1,N,IOP2,M,DIST,AZIM,IMAX)
1550
1560 410    IF(IOP2.EQ.0) GO TO 500
1570      IF(IOP2.EQ.1) CALL TAHDUM (M,IMAX)
1580      IF(IOP2.EQ.2) CALL SUMARY (JMAX,ISUM)
1590      IF(IOP2.EQ.3) CALL SUMTWC (M,N)
1600      IF(IOP2.EQ.7) CALL CARRYC (M,N,LNIMAX)
1610      JMAX=0
1620      IF(IOP1.EQ.0) GO TO 1
1630      GO TO 600
1640

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```

1650 500 IF(IOP1.EQ.1.OR.IOP1.EQ.2) CALL CONTRU (I,J,M,N,IMAX,AFAC)
1660
1670 600 CALL OPRIN1 (I,J,M,N,IMAX,SNDF,SSND,CFAC,IOP1)
1680
1690 CALL STATS (M,SNDF,SSND)
1700
1710 IF(IPUN.EQ.1) CALL OPUNCH (M,N,IMAX,DIST,AZIM)
1720
1730 GO TO 1
1740 800 FORMAT(A64)
1750 810 FORMAT(V)
1760 895 FURMAT (1H1)
1770 999 STOP
1780 END
1790 SUBROUTINE RINPUT (IOP1,N,IOP2,M,DIST,AZIM,IMAX)
1800
1810 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
1820 & SFGS(50,20),DFGS(50,20),TK(50,20),VA(50,20),DP(50,20)
1830 & ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
1840 COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
1850 & ,VC(20,20)
1860 COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
1861 CHARACTER*60 TITLE
1870
1880 PRINT 51, TITLE
1890 51 FORMAT(T2,"CROSSHOLE DATA =",A60,/)
1900
1910 PRINT 800, DIST
1920 800 FORMAT ( 5X,36H HORIZONTAL DISTANCE BETWEEN HOLES IS,F6.1,/)
1930
1940 IF(IOP1.NE.5) GO TO 600
1950 GZ(1)=DELGS
1960 SZ(1)=DELGS
1970 DO 500 J=2,M
1980 SZ(J)=SZ(J-1)+DELGS
1990 500 GZ(J)=GZ(J-1)+DELGS
2000
2010 600 PRINT 810
2020 810 FORMAT(6X,5HDEPTH,4X,6HDIRECT,1X,7HARRIVAL,3X,8HAPPARENT,
2030 & 5X,9HSHOT HOLE,5X,6HGEO HOLE,/,2X,4HSHOT,4X,3HGEO,2X,
2040 & 8HDISTANCE,1X,4HTIME,3X,4HVELO,6X,5HX=DEV,3X,5HY=DEV,
2050 & 3X,5HX=DEV,3X,5HY=DEV,/)
2060
2070 ANGLE=0.01745*AZIM
2080 XFAC=DIST*COS(ANGLE)
2090 YFAC=DIST*SIN(ANGLE)
2100
2110 DO 100 J=1,M
2120
2130 SX(J)=0.0
2140 SY(J)=0.0
2150 GX(J)=0.0
2160 100 GY(J)=0.0
2170
2180 IF(IOP1.EQ.5) GO TO 300

```

```

2190      DO 250 J=1,M
2200      IF (IOP1.EQ.1.OR.IOP1.EQ.3) READ (1,820)LIN,SZ(J),SX(J),SY(J),GZ(J),
2210      &      GX(J),GY(J)
2220      IF (IOP1.EQ.2.OR.IOP1.EQ.4) READ (1,830)LIN,SZ(J),SX(J),SY(J),GZ(J),
2230      &      GX(J),GY(J)
2240 250  CONTINUE
2245      DO 6 J=1,M
2250      IF (IOP1.EQ.1.OR.IOP1.EQ.3)READ (1,820)LIN,TR(J,N)
2260      IF (IOP1.EQ.2.OR.IOP1.EQ.4) READ (1,820)LIN,VA(J,N)
2265 6    CONTINUE
2270      IF (IOP1.EQ.2.OR.IOP1.EQ.4) GO TO 300
2280      DO 5 J=1,M
2290 5    TR(J,N)=TR(J,N)/1000.
2300 300  DO 200 J=1,M
2310      DFGS(J,N)=GZ(J)-SZ(J)
2320      SFGS(J,N)=(GX(J)+XFAC-SX(J))*(GX(J)+XFAC-SX(J))
2330      SFGS(J,N)=SFGS(J,N)+(GY(J)+YFAC-SY(J))*(GY(J)+YFAC-SY(J))
2340      SFGS(J,N)=SQRT(SFGS(J,N))
2350      SS(J,N)=0.0
2360      SG(J,N)=SS(J,N)+SFGS(J,N)
2370      DS(J,N)=SZ(J)
2380      DG(J,N)=GZ(J)
2390      HYPOSQ=DFGS(J,N)*DFGS(J,N)+SFGS(J,N)*SFGS(J,N)
2400      DP(J,N)=SQRT(HYPOSQ)
2410      IF (IOP1.EQ.1.OR.IOP1.EQ.3) VA(J,N)=DP(J,N)/TR(J,N)
2420      IF (IOP1.EQ.2.OR.IOP1.EQ.4) TR(J,N)=DP(J,N)/VA(J,N)
2430      IF (IOP1.EQ.5) VA(J,N)=0.0
2440      IF (IOP1.EQ.5) TR(J,N)=0.0
2450 200  PRINT 840, DS(J,N),DG(J,N),DP(J,N),TR(J,N),VA(J,N),SX(J),SY(J),
2460      &      GX(J),GY(J)
2470
2480      IF (IOP1.EQ.1.OR.IOP1.EQ.2) GO TO 900
2490      READ (1,850) LIN,(DL(I,N),I=1,IMAX=1)
2500      READ (1,850)LIN,(VL(I,N),I=1,IMAX)
2510 860  FORMAT (/,32H SPECIFIED TRUE VELOCITY PROFILE      )
2520      PRINT 860
2530      DO 400 I=1,IMAX=1
2540 400  PRINT 865, VL(I,N),DL(I,N)
2550      PRINT 865, VL(IMAX,N)
2560 865  FORMAT (20X,F9.1,/,50X,F9.1)
2570      RETURN
2580
2590 900  CONTINUE
2600      IF (VFIRST.GT.0.0) PRINT 872, VFIRST
2610      IF (VLAST.GT.0.0) PRINT 874, VLAST
2620      IF (DLLAST.GT.0.0) PRINT 876, DLLAST
2630      RETURN
2640 872  FORMAT (/,10X,50H THE FIRST LAYER TRUE VELOCITY WAS SPECIFIED TO BE
2650      &      ,F8.0)
2660 874  FORMAT (/,10X,52H THE DEEPEST LAYER TRUE VELOCITY WAS SPECIFIED TO
2670      &      ,F8.0)
2680 876  FORMAT ( /,10X,51H THE DEPTH TO THE DEEPEST LAYER WAS SPECIFIED TO B
2690      &      ,F7.1)
2700 820  FORMAT(V)
2710 830  FORMAT(V)

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2720 840 FORMAT (T1,F6.1,T8,F6.1,T15,F6.1,T22,F7.4,T30,F7.0,T38,
2730 &2F8.2,T55,2F8.2)
2740 850 FORMAT(V)
2750 END
2760 SUBROUTINE CONTRU (I,J,M,N,IMAX,AFAC)
2770
2780 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
2790 & SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
2800 COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
2810 COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
2811 CHARACTER*60 TITLE
2820
2830 PRINT 110,TITLE
2840 110 FORMAT (///,T2,"CROSSHOLE DIAGNOSTIC =",A60,///)
2850
2860 I=1
2870 J=1
2880 IF(VFIRST.LE.0.0) GO TO 300
2890 IF(VFIRST.GT.0.0) PRINT 810, VFIRST
2900 810 FORMAT ( 2X,59HCAUTION = THE FIRST LAYER TRUE VELOCITY WAS SPECIFI
2910 &ED TO BE ,F7.0)
2920 IF(VA(1,N)/VA(2,N).GT.1.0-AFAC.AND.VA(1,N)/VA(2,N).LT.1.0+AFAC) GO
2930 &TO 100
2940 GO TO 700
2950
2960 100 PRINT 820, VA(1,N),DG(1,N),VA(1,N),DG(1,N)
2970 820 FORMAT(12X,18HHOWEVER, SINCE THE,F7.0,3H AT,F6.1,21H IS APPARENTLY
2980 & A TRUE/12X,57HVELOCITY, THE INTERFACE BETWEEN THE SPECIFIED FIRST
2990 & LAYER/12X,17HTRUE VELOCITY AND,F7.0,22H MAY BE SHALLOWER THAN,F6.
3000 &1,8H. CHECK/12X,45HSEISMIC REFRACTION DATA FOR THIS POSSIBILITY.)
3010 300 IF(J.EQ.M) GO TO 400
3020 IF(J.GT.M) RETURN
3030 AR=VA(J,N)/VA(J+1,N)
3040 IF(AR.GT.1.0-AFAC.AND.AR.LT.1.0+AFAC) GO TO 400
3050 IF(AR.LE.1.0-AFAC) GO TO 700
3060 IF(AR.GE.1.0+AFAC) GO TO-200
3070
3080 400 VL(I,N)=VA(J,N)
3090 SVL(I,N)=SVL(I,N)+VL(I,N)
3100 K(I,N)=K(I,N)+1
3110 IMAX=I
3120 J=J+1
3130 GO TO 300
3140
3150 200 CALL UPTIME (I,J,M,N,IMAX)
3160 GO TO 300
3170
3180 700 CALL DOWNTM(I,J,M,N,IMAX)
3190 GO TO 300
3200
3210 RETURN
3220 END
3230 SUBROUTINE UPTIME(I,J,M,N,IMAX)
3240
3250 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),

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```

3260      &          SFGS(50,20),DFGS(50,20),TK(50,20),VA(50,20),DP(50,20)
3270      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20)
3280
3290C *** LOCATES INTERFACE FOR VELOCITIES DECREASING WITH DEPTH *****
3300
3310      IF(DG(J,N).EQ.DG(J+1,N).AND.DS(J,N).LE.DG(J+1,N)) GO TO 260
3320      JB=1
3330 205 JUU=J+JB
3340
3350C *****
3360      PRINT 200, I,J,JB
3370 200 FORMAT (25X,'EXECUTION CHECK = LAYER',I3,' = DEPTH',I3,
3380      & ' = UP',I2)
3390C *****
3400
3410      VL(I,N)=VA(J,N)
3420      VL(I+1,N)=VA(JUU,N)
3430      DL(I,N)=TR(J+1,N)
3440      ADJSQ=VL(I,N)*VL(I,N)=VL(I+1,N)*VL(I+1,N)
3450      ADJ=SQRT(ADJSQ)
3460      DL(I,N)=DL(I,N)=SFGS(J+1,N)/VL(I,N)
3470      DL(I,N)=DL(I,N)*VL(I,N)/ADJ
3480      DL(I,N)=0.5*DL(I,N)*VL(I+1,N)
3490      DL(I,N)=DL(I,N)=0.5*DFGS(J+1,N)
3500      DL(I,N)=DG(J+1,N)=DFGS(J+1,N)=DL(I,N)
3510      IF(DL(I,N).GT.DG(J,N).AND.DL(I,N).LE.DG(J+1,N)) GO TO 280
3520      IF(JUU.EQ.M) GO TO 280
3530      IF(VA(JUU,N).LT.VA(JUU+1,N)) GO TO 280
3540      JB=JB+1
3550      GO TO 205
3560
3570 280 IF(DL(I,N).GT.DG(J,N).AND.VA(J,N).EQ.VL(I,N).AND.
3580      &VA(J+1,N).EQ.VL(I+1,N)) PRINT 527, DL(I,N),DG(J,N),DL(I,N)
3590      IF(DL(I,N).GT.DG(J+1,N).OR.DL(I,N).LE.DG(J,N)) DL(I,N)=DG(J,N)+1.0
3600      SVL(I,N)=SVL(I,N)+VL(I,N)
3610      K(I,N)=K(I,N)+1
3620      K(I+1,N)=K(I+1,N)+JB-1
3630      SVL(I+1,N)=SVL(I+1,N)+(JB-1)*VL(I+1,N)
3640      IMAX=I
3650      I=I+1
3660      J=J+JB
3670 527 FORMAT(T3,'CAUTION = THE INTERFACE CALCULATED TO BE AT',F6.1,
3680      &/T5,'COULD BE ANYWHERE BETWEEN',F6.1,' AND',F6.1)
3690      RETURN
3700
3710 260 PRINT 550, VA(J,N),DG(J,N),VA(J+1,N),DG(J+1,N)
3720 550 FORMAT(T3,'CAUTION = THE',F7.0,' AT GEOPHONE DEPTH',F6.1,
3730      &'AND THE',F7.0,' AT GEOPHONE DEPTH',F6.1,' SHOULD BE EQUAL.')
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3810 SUBROUTINE DOWNTM(I,J,M,N,IMAX)
3820
3830 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
3840 & SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
3850 COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20)
3860 COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
3861 CHARACTER*60 TITLE
3870
3880C *** LOCATES INTERFACE FOR VELOCITIES INCREASING WITH DEPTH *****
3890
3900 JA=1
3910 705 JJJ=J+JA-1
3920
3930C *****
3940 PRINT 200, I,J,JA
3950 200 FORMAT(25X,'EXECUTION CHECK = LAYER',I3,' = DEPTH',I3,
3960 & ' ? = DOWN',I2)
3970C *****
3980
3990 VL(I,N)=VA(J,N)
4000 VL(I+1,N)=VA(J+JA,N)
4010 IF(I,EQ,1,AND,VFIRST,GT,0,0,AND,J,EQ,1) VL(1,N)=VFIRST
4020 IF(J+JA,GT,M,AND,VLAST,GT,0,0) VL(I+1,N)=VLAST
4030
4040 DL(I,N)=TR(JJJ,N)
4050 ADJSQ=VL(I+1,N)*VL(I+1,N)-VL(I,N)*VL(I,N)
4060 IF(ADJSQ,LE,0,0) PRINT 501, DG(J,N)
4070 ADJ=SQRT(ADJSQ)
4080 DL(I,N)=DL(I,N)-SFGS(J,N)/VL(I+1,N)
4090 IF(DL(I,N),LT,0,0) PRINT 503, DG(J,N)
4100 DL(I,N)=DL(I,N)*VL(I+1,N)/ADJ
4110 DL(I,N)=0,5*DL(I,N)*VL(I,N)
4120 DL(I,N)=DL(I,N)-0,5*DFGS(J,N)
4130 IF(DL(I,N),LT,0,0) PRINT 505, DG(J,N)
4140
4150 DL(I,N)=DL(I,N)+DFGS(JJJ,N)+DS(JJJ,N)
4160 IF(DG(J+JA,N),NE,DG(JJJ,N),AND,DL(I,N),LE,DG(J+JA,N),AND,
4170 & DL(I,N),GT,DG(JJJ,N)) GO TO 720
4180 IF(DG(J+JA,N),EQ,DG(JJJ,N),AND,DL(I,N),LE,DS(J+JA,N),AND,
4190 & DL(I,N),GT,DS(JJJ,N)) GO TO 720
4200 IF(J+JA,EQ,M,AND,VLAST,GT,0,0) GO TO 710
4210 IF(J+JA,GE,M) GO TO 780
4220 IF(VA(J+JA,N),GT,VA(J+JA+1,N)) GO TO 780
4230 710 JA=JA+1
4240 GO TO 705
4250
4260 720 IF(JA,EQ,1,AND,J+2,LE,M) CALL DTCHK (I,J,M,N,JA)
4270
4280 780 IF(J+JA,GT,M) GO TO 790
4290 IF(DL(I,N),LT,DG(J+1,N),AND,VA(J,N),EQ,VL(I,N),AND,
4300 & VA(J+1,N),EQ,VL(I+1,N)) PRINT 527, DL(I,N),DL(I,N),DG(J+1,N)
4310 IF(J+JA,EQ,M,AND,DL(I,N),GT,DG(J+JA,N)) PRINT 525
4320 & ,DG(JJJ,N),VA(JJJ,N),VA(J+JA,N),DG(J+JA,N)
4330 IF(J+JA,LT,M,AND,DL(I,N),GT,DG(J+JA,N),AND,
4340 & VA(J+JA,N),GT,VA(J+JA+1,N)) PRINT 530, DG(JJJ,N),VA(JJJ,N),

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4350      &      VA(J+JA,N),DG(J+JA,N),VA(J+JA+1,N),DG(J+JA+1,N)
4360
4370      IF(DL(I,N).GT.DG(J+JA,N).OR.DL(I,N).LT.DG(JJJ,N))
4380      &DL(I,N)=DG(J+JA,N)
4390
4400      IF(DL(I,N).GT.DS(J+JA,N).OR.DL(I,N).LT.DS(JJJ,N).AND.
4410      &      DG(J+JA,N).EQ.DG(JJJ,N)) DL(I,N)=DS(J+JA,N)
4420
4430 790 SVL(I,N)=SVL(I,N)+JA*VL(I,N)
4440      K(I,N)=K(I,N)+JA
4450      IMAX=I
4460      IF(J+JA.GT.M.AND.VLAST.GT.0.0.AND.DLLAST.GT.0.0) GO TO 800
4470      I=I+1
4480      J=J+JA
4490      RETURN
4500
4510 800 PRINT 810,DLLAST,DL(I,N)
4520      IMAX=I+1
4530      SVL(IMAX,N)=VLAST
4540      K(IMAX,N)=1
4550      J=J+JA
4560      RETURN
4570 501 FORMAT (T13,"AT GEOPHONE DEPTH",F6.1," NEGATIVE VELOCITY DIFFEREN
4580      &CE")
4590 503 FORMAT (T13,"AT GEOPHONE DEPTH",F6.1," NEGATIVE TIME FACTOR")
4600 505 FORMAT (T13,"AT GEOPHONE DEPTH",F6.1," NEGATIVE DEPTH FACTOR")
4610 525 FORMAT (T3,"CAUTION = AT GEOPHONE DEPTH",F6.1," THE",F7.0,"
4620      &" COULD BE APPARENT",T13,"AND OR THE",F7.0,"
4630      &" SHOULD BE APPARENT")
4640 527 FORMAT(T3,"CAUTION = THE INTERFACE CALCULATED TO BE AT",F6.1," CO
4650      &ULD BE ANYWHERE BETWEEN",F6.1," AND",F6.1)
4660 528 FORMAT (T3,"CAUTION = AT GEOPHONE DEPTH",F6.1," IF THE",F7.0," IS
4670      & A CORRECT VELOCITY ,",F7.0," THEN THE ",F7.0," AT GEOPHONE DEPTH",F7.0,"
4680      &F6.1," IS EITHER APPARENT OR INCORRECT.")
4690 530 FORMAT ( 2X,"CAUTION = AT GEOPHONE DEPTH",F6.1, 4H THE,F7.0,
4700      & 18H COULD BE APPARENT,,/12X,10HAND/OR THE,F7.0, 3H AT,F6.1,
4710      & 7H OR THE,F7.0,/3H AT,F6.1,14H ARE INCORRECT)
4720 810 FORMAT(2X,"CAUTION = THE EDPTH TO THE HIGH VELOCITY LAYER BENEATH
4730      &THE ",F7.0," DEEPEST GEOPHONE WAS SPECIFIED TO BE ",F7.1,
4740      &" AND CALCULATED TO BE ",F7.1)
4750      END
4760      SUBROUTINE DTCHEK (I,J,M,N,JA)
4770
4780      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
4790      &      SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
4800      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
4810      COMMON/CONSTA/DELGS,VFIRST,VLAST,DLLAST,TITLE
4811      CHARACTER*60 TITLE
4820
4830C *** CHECKS DOWNTM INTERPRETATION FOR POSSIBLE AMBIGUITIES AND
4840C      ASSUMES THE SIMPLIEST INTERPRETATION *****
4850
4860      IF(VA(J,N).GT.VA(J+2,N).OR.VA(J+1,N).GT.VA(J+2,N)) RETURN
4870      IF(DS(J+1,N).LT.DS(J,N).AND.DG(J+1,N).GT.DG(J,N)) RETURN
4880

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4890     L=0
4900     IF (J, EQ, 1) L=1
4910     IF (L, EQ, 1, AND, VFIRST, GT, 0.0) PRINT 528, DG(1, N)
4920     528 FORMAT(1X, 64HNOTE==THE FIRST LAYER TRUE VELOCITY WAS NOT SEI
4930     &EQUAL TO VFIRST, /7X, 52HCHECK SEISMIC REFRACTION DATA FOR POSSIBLE
4940     &INTERFACE/7X, 25HAT A SHALLOWER DEPTH THAN, F6.1)
4950     V2CH=VA(J+1, N)
4960     V3CH=VA(J+2, N)
4970
4980     D2MN=TR(J+1, N)
4990     ADJSQ=V3CH*V3CH-V2CH*V2CH
5000     IF (ADJSQ, LE, 0.0) GO TO 728
5010     ADJ=SQRT(ADJSQ)
5020     GO TO 729
5030     728 ADJ=0.0
5040     729 CONTINUE
5050     D2MN=D2MN-SFGS(J+1, N)/V3CH
5060     D2MN=D2MN*V3CH/ADJ
5070     D2MN=0.5*D2MN*V2CH
5080     D2MN=D2MN-0.5*DFGS(J+1, N)
5090     D2MN=D2MN+DFGS(J+1, N)+DS(J+1, N)
5100
5110     IF (DG(J+1, N), NE, DG(J+2, N), AND, D2MN, GT, DG(J+1, N), AND,
5120     & D2MN, LT, DG(J+2, N)) PRINT 529, DG(J+1, N), VA(J+1, N)
5130     IF (DG(J+1, N), EQ, DG(J+2, N), AND, D2MN, GT, DS(J+1, N), AND,
5140     & D2MN, LT, DS(J+2, N)) PRINT 529, DS(J+1, N), VA(J+1, N)
5150
5160     730 IF (J=1, EQ, 0, OR, I=1, EQ, 0) GO TO 770
5170     IF (VA(J-1, N), GT, VA(J, N)) GO TO 770
5180     IF (VL(I-1, N), NE, VA(J-1, N), OR, VL(I, N), NE, VA(J, N)) GO TO 770
5190     J=J-1
5200     I=I-1
5210
5220     770 V1CH=VA(J, N)
5230     V2CH=VA(J+2, N)
5240
5250     DPEX=TR(J+1, N)
5260     ADJSQ=V2CH*V2CH-V1CH*V1CH
5270     ADJ=SQRT(ADJSQ)
5280     DPEX=DPEX-SFGS(J+1, N)/V2CH
5290     DPEX=DPEX*V2CH/ADJ
5300     DPEX=0.5*DPEX*V1CH
5310     DPEX=DPEX-0.5*DFGS(J+1, N)
5320     DPEX=DPEX+DFGS(J+1, N)+DS(J+1, N)
5330
5340     IF (DG(J+1, N), NE, DG(J+2, N), AND, DPEX, GT, DG(J+1, N), AND,
5350     & DPEX, LT, DG(J+2, N)) GO TO 790
5360     IF (DG(J+1, N), EQ, DG(J+2, N), AND, DPEX, GT, DS(J+1, N), AND,
5370     & DPEX, LT, DS(J+2, N)) GO TO 790
5380     RETURN
5390
5400     790 VL(I, N)=VA(J, N)
5410     VL(I+1, N)=VA(J+2, N)
5420     DL(I, N)=DPEX
5430     JA=2

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5440 529 FORMAT (T3,"CAUTION * AT GEOPHONE DEPTH",F6.1," THE",F7.0," COULD
5450 & BE A TRUE VELOCITY.")
5460 RETURN
5470 END
5480 SUBROUTINE DPHIN1 (I,J,M,N,IMAX,SNDF,SSND,CFAC,KTYPE)
5490
5500 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
5510 & SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
5520 COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
5530 & VC(20,20)
5540 COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
5541 CHARACTER*60 TITLE
5550
5560C *** OUTPUT PRINTOUT *****
5570
5580 PRINT 114, TITLE
5590 114 FORMAT(///,T2,"CROSSHOLE INTERPRETATION =",A60)
5600
5610 PRINT 805
5620 805 FORMAT(///,T4,"<INTERFACE DEPTH>",/T2,"GEO",T8,"SHOT",T16,"TRUE",T27,
5630 & "COMPUTED TRAVEL TIMES, SECONDS",T67,"APPARENT",
5640 & /T2,"DEPTH DEPTH VELOCITY",T67,"APPARENT",
5650 & T24,"DIRECT",T32,"DOWN",T40,"DOWN",T48,"DOWN",T56,"UP",
5660 & T64,"COMPUTED",T72,"MEASURED",/T32,"1LAYER",T40,"2LAYER",
5670 & T48,"3LAYER",T56,"1LAYER",///)
5680 IF(KTYPE.EQ.1.OR.KTYPE.EQ.2) CALL TRUAV1 (IMAX,CFAC,N)
5690
5700
5710 I=1
5720 DO 890 J=1,M
5730 818 IF(DL(I,N).GT.DG(J,N)) GO TO 830
5740 IF(I.EQ.IMAX) GO TO 830
5750 820 FORMAT(T5,"<",T6,F6.1,T12,">")
5760 PRINT 820, DL(I,N)
5770
5780 IF(I+1.EQ.IMAX) GO TO 824
5790 IF(DG(J,N).GE.DL(I+1,N)) PRINT 822, VL(I+1,N)
5800 821 IF(DG(J,N) .LT. DL(I+1,N)) GO TO 824
5810#822 FORMAT(16X,F7.0)
5820 I=I+1
5830 GO TO 818
5840#824 I=I+1
5850
5860 830 CALL TRTIM2(I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4)
5870 TT2U=999.
5880 IF(VL(I,N).GT.VL(I-1,N)) GO TO 827
5890 TT2U=SFGS(J,N)/VL(I-1,N)
5900 ADJSQ=VL(I-1,N)*VL(I-1,N)-VL(I,N)*VL(I,N)
5910 VV=SQRT(ADJSQ)
5920 TT2U=TT2U+(DFGS(J,N)+2.0*(DG(J,N)=DL(I-1,N)))*VV/(VL(I-1,N)*VL(I,N)
5930 &))
5940
5950 827 TMIN=AMIN1(TT1,TT2,TT3,TT4,TT2U)
5960 VLA=DP(J,N)/TMIN
5970 VC(J,N)=VLA

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5980
5990     CALL FOROUT (I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4,SNDF,SSND,VLA,IT2U,
6000     & TMIN)
6010
6020 890 CONTINUE
6030
6040     IF(I,GE,IMAX) GOTO900
6050     PRINT 820,DL(I,N)
6060     PRINT 840,VL(I+1,N)
6070 840     FORMAT(T17,F7,0)
6080
6090 900 RETURN
6100     END
6110     SUBROUTINE TRUAV1(IMAX,CFAC,N)
6120
6130     COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20)
6140     COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
6141     CHARACTER*60 TITLE
6150
6160C *** CONVERTS DETAILED LAYERING INTO REPRESENTATIVE LAYERING *****
6170
6180 809 IC=0
6190     DO 806 I=1,IMAX
6200 806 VL(I,N)=SVL(I,N)/K(I,N)
6210
6220     DO 808 I=1,IMAX-1
6230     IF(I,GE,IMAX-IC-1) GO TO 808
6240     RIR=VL(I,N)/VL(I+1,N)
6250     IF(K(I,N).GT,1,OR,K(I+1,N).GT,1) BFAC=0,05
6260     IF(K(I,N).EQ,1,AND,K(I+1,N).EQ,1) BFAC=0,10
6270     IF(RIR.LT,1,0-BFAC,OR,RIR.GT,1,0+BFAC) GO TO 808
6280     SVL(I,N)=SVL(I,N)+SVL(I+1,N)
6290     K(I,N)=K(I,N)+K(I+1,N)
6300     VL(I,N)=SVL(I,N)/K(I,N)
6310     IF(I+1,EQ,IMAX) GO TO 808
6320     DL(I,N)=DL(I+1,N)
6330
6340     DO 807 II=I+1,IMAX-IC-1
6350     SVL(II,N)=SVL(II+1,N)
6360     K(II,N)=K(II+1,N)
6370     VL(II,N)=VL(II+1,N)
6380     IF(II,EQ,IMAX-IC-1) GO TO 807
6390     DL(II,N)=DL(II+1,N)
6400 807 CONTINUE
6410     IC=IC+1
6420 808 CONTINUE
6430
6440     IMAX=IMAX-IC
6450     IF(IC,GE,1) GO TO 809
6460
6470     IF(VLAST,EQ,0,0) RETURN
6480     IF(VLAST,GT,0,0,AND,VL(IMAX,N),EQ,VLAST) RETURN
6490     IF(DLLAST,EQ,0,0) RETURN
6500     DL(IMAX,N)=DLLAST
6510     IMAX=IMAX+1

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6520      VL(IMAX,N)=VLAST
6530
6540      RETURN
6550      END
6560      SUBROUTINE TRTIM2(I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4)
6570
6580      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
6590      &          SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
6600      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
6610
6620C *** COMPUTES TRAVEL TIMES FROM A TRUE VELOCITY PROFILE *****
6630
6640      TT(1)=999.
6650      TT(2)=999.
6660      TT(3)=999.
6670      TT(4)=999.
6680      NL=1
6690      TT(NL)=DP(J,N)/VL(I,N)
6700      IF(I,EQ,IMAX) GO TO 840
6710      IF(VL(I,N),GT,VL(I+1,N)) TT(2)=777.
6720      LF=0
6730      LC=0
6740
6750 835 LC=LC+1
6760      NL=LC+1
6770      IF(TT(2),EQ,777,AND,NL,EQ,2) GO TO 835
6780      TT(NL)=SFGS(J,N)/VL(I+LC,N)
6790      ADJSQ=VL(I+LC,N)*VL(I+LC,N)-VL(I,N)*VL(I,N)
6800      ADJSQ=ABS(ADJSQ)
6810      ADJ=SQRT(ADJSQ)
6820      TT(NL)=TT(NL)+(DFGS(J,N)+2.0*(DL(I,N)-DG(J,N)))*ADJ/(VL(I+LC,N)*
6830      &VL(I,N))
6840      IF(I+1,EQ,IMAX) TT(3)=999.
6850      IF(I+1,EQ,IMAX) GO TO 840
6860      IF(VL(I+1,N),GT,VL(I+2,N)) TT(3)=777.
6870      IF(TT(3),EQ,777,AND,NL,EQ,3) GO TO 835
6880      IF(LC,EQ,1) GO TO 835
6890
6900 837 ADJSQ=VL(I+LC,N)*VL(I+LC,N)-VL(I+LC-LF-1,N)*VL(I+LC-LF-1,N)
6910      ADJSQ=ABS(ADJSQ)
6920      ADJ=SQRT(ADJSQ)
6930      TT(NL)=TT(NL)+2.0*(DL(I+LC-LF-1,N)-DL(I+LC-LF-2,N))*ADJ/(VL(I+LC,N)
6940      &)*VL(I+LC-LF-1,N))
6950      IF(I+2,EQ,IMAX) TT(4)=999.
6960      IF(I+2,EQ,IMAX) GO TO 840
6970      IF(VL(I+2,N),GT,VL(I+3,N)) TT(4)=999.
6980      IF(LC,EQ,2) GO TO 835
6990      LF=LF+1
7000      IF(LC,EQ,3,AND,LF,EQ,1) GO TO 837
7010
7020 840 TT1=TT(1)
7030      TT2=TT(2)
7040      TT3=TT(3)
7050      TT4=TT(4)
7060      RETURN

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```

7070      END
7080      SUBROUTINE STATS(M,SNDF,SSND)
7090
7100C    *** COMPUTES THE MEAN AND STANDARD DEVIATION *****
7110
7120      XM=FLOAT(M)
7130      ANDF=SNDF/XM
7140      SSND=SSND/(XM-1,0)
7150      STD=SQRT(SSND)
7160
7170      PRINT 894, ANDF,STD
7180      894 FORMAT (///,T50,'MEAN DIFFERENCE =',F6,2,' *',/,
7190      &T33,'STANDARD DEVIATION OF DIFFERENCE =',F6,2,' *',/,
7200      &T38,'* PERCENT OF MEASURED VELOCITY')
7210
7220      SNDF=0,0
7230      SSND=0,0
7240
7250      RETURN
7260      END
7270      SUBROUTINE FOROUT (I,J,M,N,IMAX,NL,TT1,TT2,TT3,TT4,SNDF,SSND,VLA,
7280      & TT2U,TMIN)
7290
7300      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
7310      & SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
7320      & SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
7330      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
7340      & VC(20,20)
7350      COMMON /CONST/ DELGS,VFIRST,VLAST,DLLAST,TITLE
7351      CHARACTER *60 TITLE
7360
7370      IF(VA(J,N)) 500,500,400
7380
7390      400 DIFN=VLA=VA(J,N)
7400      DIFN=DIFN*100,0/VA(J,N)
7410      SNDF=SNDF+DIFN
7420      SSND=SSND+DIFN*DIFN
7430
7440      500 IF(VA(J,N),EQ,0,0) DIFN=0,0
7450      IF(TT2U,NE,999) GO TO 200
7460      IF(TT2,EQ,777,AND,TT3,EQ,777,AND,TT4,EQ,999)
7470      &PRINT 885, DG(J,N),DS(J,N),VL(I,N),TT1,
7480      &VLA,VA(J,N)
7490      IF(TT2,NE,777,AND,TT3,EQ,777,AND,TT4,EQ,999)
7500      &PRINT 875, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,
7510      &VLA,VA(J,N)
7520      IF(TT2,EQ,777,OR,TT3,EQ,777) GO TO 100
7530      IF(TT2,EQ,999,AND,TT3,EQ,999,AND,TT4,EQ,999)
7540      &PRINT 885, DG(J,N),DS(J,N),VL(I,N),TT1,
7550      &VLA,VA(J,N)
7560      IF(TT2,NE,999,AND,TT3,EQ,999,AND,TT4,EQ,999)
7570      &PRINT 875, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,
7580      &VLA,VA(J,N)
7590      IF(TT2,NE,999,AND,TT3,NE,999,AND,TT4,EQ,999)
7600      &PRINT 865, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,

```

```
7610      &VLA,VA(J,N)
7620      IF (TT2,NE,999,AND,TT3,NE,999,AND,TT4,NE,999)
7630      &PRINT 855, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,TT4,
7640      &VLA,VA(J,N)
7650
7660 100 CONTINUE
7670      IF (TT2,EQ,777,AND,TT3,EQ,999,AND,TT4,EQ,999)
7680      &PRINT 885, DG(J,N),DS(J,N),VL(I,N),TT1,
7690      &VLA,VA(J,N)
7700      IF (TT2,EQ,777,AND,TT3,EQ,999,AND,TT4,EQ,999) GO TO 888
7710      IF (TT2,EQ,777,AND,TT3,NE,777,AND,TT4,EQ,999)
7720      &PRINT 711, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,
7730      &VLA,VA(J,N)
7740      IF (TT2,EQ,777,AND,TT3,NE,777,AND,TT4,NE,999)
7750      &PRINT 712, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,TT4,
7760      &VLA,VA(J,N)
7770      IF (TT2,EQ,777,AND,TT3,EQ,777,AND,TT4,NE,999)
7780      &PRINT 713, DG(J,N),DS(J,N),VL(I,N),TT1,TT4,
7790      &VLA,VA(J,N)
7800      IF (TT2,NE,777,AND,TT3,EQ,777,AND,TT4,NE,999)
7810      &PRINT 714, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT4,
7820      &VLA,VA(J,N)
7830      GO TO 888
7840
7850 200 CONTINUE
7860      IF (TT2,EQ,777,OR,TT3,EQ,777) GO TO 300
7870      IF (TT2,EQ,999,AND,TT3,EQ,999,AND,TT4,EQ,999)
7880      &PRINT 889, DG(J,N),DS(J,N),VL(I,N),TT1,TT2U,
7890      &VLA,VA(J,N)
7900      IF (TT2,NE,999,AND,TT3,EQ,999,AND,TT4,EQ,999)
7910      &PRINT 878, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT2U,VLA,VA(J,N)
7920      IF (TT2,NE,999,AND,TT3,NE,999,AND,TT4,EQ,999)
7930      &PRINT 868, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,TT2U,
7940      &VLA,VA(J,N)
7950      IF (TT2,NE,999,AND,TT3,NE,999,AND,TT4,NE,999)
7960      &PRINT 858, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT3,TT4,TT2U,
7970      &VLA,VA(J,N)
7980
7990 300 CONTINUE
8000      IF (TT2,EQ,777,AND,TT3,EQ,999,AND,TT4,EQ,999)
8010      &PRINT 889, DG(J,N),DS(J,N),VL(I,N),TT1,TT2U,
8020      &VLA,VA(J,N)
8030      IF (TT2,EQ,777,AND,TT3,EQ,999,AND,TT4,EQ,999) GO TO 888
8040      IF (TT2,NE,777,AND,TT3,EQ,777,AND,TT4,EQ,999)
8050      &PRINT 878, DG(J,N),DS(J,N),VL(I,N),TT1,TT2,TT2U,VLA,VA(J,N)
8060      IF (TT2,EQ,777,AND,TT3,NE,777,AND,TT4,EQ,999)
8070      &PRINT 721, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,TT2U,
8080      &VLA,VA(J,N)
8090      IF (TT2,EQ,777,AND,TT3,NE,777,AND,TT4,NE,999)
8100      &PRINT 722, DG(J,N),DS(J,N),VL(I,N),TT1,TT3,TT4,TT2U,
8110      &VLA,VA(J,N)
8120      IF (TT2,EQ,777,AND,TT3,EQ,777,AND,TT4,NE,999)
8130      &PRINT 723, DG(J,N),DS(J,N),VL(I,N),TT1,TT4,TT2U,
8140      &VLA,VA(J,N)
8150      IF (TT2,NE,777,AND,TT3,EQ,777,AND,TT4,NE,999)
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8160      &PRINT 724, DG(J,N),DS(J,N),VL(1,N),TT1,TT2,TT4,TT2U,
8170      &VLA,VA(J,N)
8180
8190 888 CONTINUE
8200
8210 711 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T64,2F8.0)
8220 712 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T48,F7.4,
8230      &T64,2F8.0)
8240 713 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T48,F7.4,T64,2F7.4)
8250 714 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T48,F7.4,164,2F8.0)
8260 721 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T56,F7.4,164,2F8.0)
8270 722 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T40,F7.4,T48,
8280      &F7.4,T56,F7.4,T64,2F8.0)
8290 723 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T48,F7.4,T56,F7.4,164,2F8.0)
8300 724 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,
8310      &T48,F7.4,T56,F7.4,T64,2F8.0)
8320 855 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,
8330      &T48,F7.4,T64,2F8.0)
8340 858 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,
8350      &T48,F7.4,T56,F7.4,T64,2F8.0)
8360 865 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,164,2F8.0)
8370 868 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T40,F7.4,
8380      &T56,F7.4,T64,2F8.0)
8390 875 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T64,2F8.0)
8400 878 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T32,F7.4,T56,F7.4,164,2F8.0)
8410 885 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T64,2F8.0)
8420 889 FORMAT(T2,F6.1,T9,F6.1,T16,F7.0,T24,F7.4,T56,F7.4,T64,2F8.0)
8430
8440      RETURN
8450      END
8460      SUBROUTINE SUMARY (JMAX,ISUM)
8470      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
8480      &          SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
8490      &          ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
8500      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
8510      &,VC(20,20)
8520      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
8521      CHARACTER *60 TITLE
8530
8540C *** SETS UP TABLE FOR THREE HOLE SET P AND S WAVE DATA *****
8550
8560      CALL ARRANG (JMAX)
8570
8580
8590      PRINT 100, TITLE
8600 100 FORMAT ('1',T2,'CROSS HOLE SUMMARY =',A60,///)
8610
8620      GO TO (500,600,700), ISUM
8630
8640 500 PRINT 200
8650 200 FORMAT (T3,'SHOT GEO B GEO C', 3X,'DIRECT PATH',
8660      & 2X,'MEASURED ARRIVAL TIMES, SEC ', 6X,'TRUE',
8670      &T93,'APPARENT VELOCITY SUMMARY',
8680      &/,T3,'DEPTH DEPTH DEPTH', 4X,'DISTANCE',T68,'VELOCITY',
8690      &T90,'P-WAVE', 20X,'S-WAVE',

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8700      &/,38X,'P=WAVE', 9X,'S=WAVE',
8710      &T86,'AB',10X,'AC',11X,'AB',10X,'AC',
8720      &/,T24,'AB'   'AC',T38,'AB',5X,'AC', 6X,'AB',5X,'AC',
8730      & 4X,'P=WAVE',1X,'S=WAVE',
8740      &T82,'MEAS COMP MEAS COMP',3X,'MEAS COMP MEAS COMP',
8750      &/)
8760
8770      DO 400 J=1,JMAX
8780      400 PRINT 410, DS(J,12),DG(J,12),DG(J,13),DP(J,12),DP(J,13),
8790      & TR(J,12),TR(J,13),TR(J,14),TR(J,15),
8800      & VL(J,12),VL(J,14),
8810      & VA(J,12),VC(J,12),VA(J,13),VC(J,13),VA(J,14),VC(J,14),VA(J,15),
8820      & VC(J,15)
8830      410 FORMAT (T2,F6,1, F6,1, F6,1,1X,F6,1,1X,F6,1,T35,2F7,4,
8840      &T50,2F7,4, 1X,2F7,0, 2X,4F6,0,1X,4F6,0)
8850      GO TO 900
8860
8870      600 CONTINUE
8880
8890      PRINT 610
8900      610 FORMAT (
8910      & 24X,10MHOLE DEPTH, 4X,11HDIRECT PATH, 6X,18HARRIVAL TIMES, SEC,/,
8920      & 40X, 8HDISTANCE, 6X,6HP=WAVE, 5X, 6HS=WAVE,/,
8930      &24X,'A'   'B'   'C', 5X,'AB'   'AC', 6X,'AB'   'AC'   'AB'   'AC',
8940      &/)
8950      DO 420 J=1,JMAX
8960      420 PRINT 430, DS(J,12),DG(J,12),DG(J,13),DP(J,12),DP(J,13),
8970      & TR(J,12),TR(J,13),TR(J,14),TR(J,15)
8980      430 FORMAT (20X,3F6,1,2F7,0, 1X,2F7,4, 1X,2F7,4)
8990
9000
9010      PRINT 435
9020      435 FORMAT(/,23X, 5HDEPTH, 14X,
9030      &26HAPPARENT VELOCITY PROFILES,/,
9040      & 31X,'COMP MEAS', 3X,'COMP MEAS', 3X,'COMP MEAS', 3X,'COMP MEA
9050      &S',/)
9060      DO 440 J=1,JMAX
9070      440 PRINT 450, DS(J,12), VC(J,12),
9080      &VA(J,12),VC(J,13),VA(J,13),VC(J,14),VA(J,14),VC(J,15),VA(J,15)
9090      450 FORMAT (22X,F6,1, 4(1X,2F6,0))
9100
9110
9120      PRINT 475
9130      475 FORMAT (/,31X, 5HDEPTH, 6X,22HTRUE VELOCITY PROFILES,/,
9140      & 43X, 6HP=WAVE, 6X, 6HS=WAVE,/,
9150      & 41X, 2HAB, 6X, 2HAC, 6X, 2HAB, 6X, 2HAC //)
9160      DO 480 J=1,JMAX
9170      480 PRINT 490, DS(J,12),VL(J,12),VL(J,13),VL(J,14),VL(J,15)
9180      490 FORMAT (30X,F6,1,4F6,0)
9190
9200      700 CONTINUE
9210
9220      900 RETURN
9230      END
9240      SUBROUTINE ARRANG (JMAX)

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9250
9260 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
9270 & SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
9280 & ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
9290 COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
9300 & ,VC(20,20)
9310 COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
9311 CHARACTER *60 TITLE
9320
9330 J2=0
9340 J3=0
9350 J4=0
9360 J5=0
9370 I2=1
9380 I3=1
9390 I4=1
9400 I5=1
9410
9420 DO 450 J=1,JMAX
9430
9440 N=2
9450 J2=J2+1
9460 J3=J3+1
9470 J4=J4+1
9480 J5=J5+1
9490
9500 IF (DS(J,2)) 250,350,250
9510
9520 250 CONTINUE
9530
9540 IF (DS(J,2).LT.DS(J3,3)) J3=J3+1
9550 IF (DS(J,2).LT.DS(J4,4)) J4=J4+1
9560 IF (DS(J,2).LT.DS(J5,5)) J5=J5+1
9570
9580 350 CONTINUE
9590 CONTINUE
9600
9610 IF (DG(J3,3).LT.DG(J5,5)) DG(J3,3)=DG(J5,5)
9620 IF (DL(I2,2).LT.DG(J2,2)) I2=I2+1
9630 IF (DL(I3,3).LT.DG(J2,2)) I3=I3+1
9640 IF (DL(I4,4).LT.DG(J3,3)) I4=I4+1
9650 IF (DL(I5,5).LT.DG(J3,3)) I5=I5+1
9660 IF (DS(J,2)) 390,360,390
9670
9680 360 CONTINUE
9690
9700 IF (DL(I4,4).LT.DG(J,4)) I4=I4+1
9710 DP(J,2)=DP(J,4)
9720 DS(J,2)=DS(J,4)
9730 DG(J,2)=DG(J,4)
9740
9750 390 CONTINUE
9760
9770 DS(J,12)=DS(J2,2)
9780 DG(J,12)=DG(J2,2)
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9790      DG(J,13)=DG(J3,3)
9800      DP(J,12)=DP(J2,2)
9810      DP(J,13)=DP(J3,3)
9820      TR(J,12)=TR(J2,2)
9830      TR(J,13)=TR(J3,3)
9840      TR(J,14)=TR(J4,4)
9850      TR(J,15)=TR(J5,5)
9860      VL(J,12)=VL(I2,2)
9870      VL(J,13)=VL(I3,3)
9880      VL(J,15)=VL(I5,5)
9890      VL(J,14)=VL(I4,4)
9900      VA(J,12)=VA(J2,2)
9910      VC(J,12)=VC(J2,2)
9920      VA(J,13)=VA(J3,3)
9930      VC(J,13)=VC(J3,3)
9940      VA(J,14)=VA(J4,4)
9950      VC(J,14)=VC(J4,4)
9960      VA(J,15)=VA(J5,5)
9970      VC(J,15)=VC(J5,5)
9980      TR(J2,2)=0.0
9990      TR(J3,3)=0.0
10000     TR(J4,4)=0.0
10010     TR(J5,5)=0.0
10020     VA(J2,2)=0.0
10030     VA(J3,3)=0.0
10040     VA(J4,4)=0.0
10050     VA(J5,5)=0.0
10060
10070     450 CONTINUE
10080
10090     DO 600 N=2,5
10100     DO 600 J=1,25
10110     TR(J,N)=0.0
10120     VA(J,N)=0.0
10130     VC(J,N)=0.0
10140     DG(J,N)=0.0
10150     DS(J,N)=0.0
10160     SG(J,N)=0.0
10170     BS(J,N)=0.0
10180     DP(J,N)=0.0
10190     600 CONTINUE
10200
10210     RETURN
10220     END
10230     SUBROUTINE CARRYU (M,N,LNIMAX)
10240     COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
10250     &          SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
10260     &          ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
10270     COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
10280     & ,VC(20,20)
10290     COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
10291     CHARACTER *60 TITLE
10300
10310     NP=N+1
10320     NO=N-1

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10330      DO 100 I=1, LNIMAX
10340      DL(I,N)=DL(I,NO)
10350  100  VL(I,N)=VL(I,NO)
10360      J=0
10370      JN=1
10380      JC=1
10390  200  J=J+1
10400      IF(DS(JN,N).EQ.0.0.AND.DS(JO,NO).EQ.0.0) GO TO 600
10410      IF(DS(JN,N)=DS(JO,NO)) 300,400,500
10420
10430  300  DS(J,NP)=DS(JN,N)
10440      DG(J,NP)=DG(JN,N)
10450      JN=JN+1
10460      GO TO 200
10470
10480  400  DS(J,NP)=DS(JN,N)
10490      DG(J,NP)=DS(JN,N)
10500      JO=JO+1
10510      JN=JN+1
10520      GO TO 200
10530
10540  500  DS(J,NP)=DS(JO,NO)
10550      DG(J,NP)=DG(JO,NO)
10560
10570      JO=JO+1
10580      GO TO 200
10590
10600  600  M=J+1
10610      DO 700 JJ=1,M
10620  700  DS(JJ,N)=DS(JJ,NP)
10630      RETURN
10640      END
10650      SUBROUTINE SUMTWO (M,N)
10660
10670      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
10680      &          SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DP(50,20)
10690      &          ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
10700      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
10710      & ,VC(20,20)
10720      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
10721      CHARACTER *60 TITLE
10730
10740      PRINT 90
10750      PRINT 100
10760  100  FORMAT (/ ,30X, 7HTABLE 3,///
10770      & 25X, 6H'REAL', 5X,17HAPPARENT VELOCITY, 2X,12H'SUPPOSEDLY',/
10780      & 15X, 5HDEPTH, 2X, 13HTRUE VELOCITY, 8X, 3HFOR,
10790      & 9X, 13HTRUE VELOCITY,/
10800      & 37X, 14H 35 M SPACING ,/
10810      & 16X, 4H( M), 6X, 5H(MPS),11X, 5H(MPS),12X, 5H(MPS),//)
10820C   337X, 14H100 FT SPACING,/
10830C   416X, 4H(F1), 6X, 5H(FPS),11X, 5H(FPS),12X, 5H(FPS),//)
10840
10850      I1=1
10860      I2=1

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10870      NP=N+1
10880      DO 200 J=1,M
10890      IF(DS(J,N).GT.DL(I1,N)) I1=I1+1
10900      IF(DS(J,N).GT.DL(I2,NP)) I2=I2+1
10910 200 PRINT 110, DS(J,N),VL(I1,N),VA(J,NP),VL(I2,NP)
10920      PRINT 250
10930 250 FORMAT (//, 7X,65HNOTE = THE 'SUPPOSEDLY' TRUE VELOCITY PROFILE IS
10940      & A PLAUSIBLE, BUT,
10950      &           //,14X,      'ERRONEOUS, INTERPRETATION OF THE GIVEN APPA
10960      &HENT VELOCITY PROFILE.')
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10980      90 FORMAT (1H1)
10990 110 FORMAT (15X,F5.1, 4X,F7.0, 9X, F7.0, 9X, F7.0)
11000 310 FORMAT ( 5X, F5.1, 4X, F7.0, 4X, 2F7.0, 2X, 2F7.0)
11010
11020      PRINT 90
11030      PRINT 300
11040 300 FORMAT (/ ,20X, 7HTABLE 5,///
11050      & 5X, 5HDEPTH, 2X,13HTRUE VELOCITY, 2X,25HAPPARENT VELOCITIES (MPS)
11060      & //,6X, 4H( M), 6X, 5H(MPS), 9X, 7H 0=7 M , 8X, 8H 0=35 M ,/
11070C 1 5X, 5HDEPTH, 2X,13HTRUE VELOCITY, 2X,25HAPPARENT VELOCITIES (FPS)
11080C 2 //,6X, 4H(FT), 6X, 5H(FPS), 9X, 7H0=20 FT, 8X, 8H0=100 FT, /
11090      & 27X, 4HCOMP, 3X, 4HMEAS, 5X, 4HCOMP, 3X, 4HMEAS,//)
11100
11110      I=1
11120      DO 400 J=1,M
11130      IF(DS(J,N).GT.DL(I,N)) I=I+1
11140 400 PRINT 310, DS(J,N),VL(I,N),VC(J,N),VA(J,N),VA(J,N+1),VA(J,N+1)
11150
11160      RETURN
11170      END
11180      SUBROUTINE TABDUM(M,IMAX)
11190
11200      COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
11210      &           SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DV(50,20)
11220      &           ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
11230      COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
11240      & ,VC(20,20)
11250      COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
11251      CHARACTER *60 TITLE
11260
11270C      PRINT 130
11280
11290      PRINT 502
11300 502 FORMAT (15X,47HAPPARENT VELOCITY AS A FUNCTION OF HOLE SPACING///,
11310      &3X,26HDEPTH      TRUE      INTERFACE,11X,25HAPPARENT VELOCITIES FOR,/,
11320      &11X,16HVELOCITY  DEPTH,16X,16HHOLE SPACINGS OF,/,
11330      &12X,7HPROFILE,13X,38H 7 M    14 M    21 M    28 M    35 M ,//)
11340C 312X,7HPROFILE,13X,38H 20 FT   40 FT   60 FT   80 FT   100 FT,//)
11350
11360      I=1
11370      J=0
11380 200 J=J+1
11390      IF(J.GT.M) GO TO 600
11400      IF(DL(I,2).LT.DS(J,2)) GO TO 400
```

```

11410 300 PRINT 110, DS(J,2),VL(I,2),VA(J,2),VA(J,3),VA(J,4),VA(J,5),VA(J,6)
11420C PUNCH 110, DS(J,2),VL(I,2),VA(J,2),VA(J,3),VA(J,4),VA(J,5),VA(J,6)
11430 IF(J,EG,M) GO TO 600
11440 GO TO 200
11450 400 PRINT 120, DL(I,2)
11460C PUNCH 120, DL(I,2)
11470 I=I+1
11480 GO TO 300
11490 600 IF(I,LT,IMAX) PRINT 140, DL(I,2),VL(I+1,2)
11500
11510 100 FORMAT (6(20A4))
11520 101 FORMAT (6(13A6,A2,/))
11530 110 FORMAT (2X,F6,1,3X,F7,0,12X,5F8,0)
11540 120 FORMAT (21X,F6,1)
11550 130 FORMAT (1H1)
11560 140 FORMAT (21X,F6,1,/,11X,F7,0)
11570
11580 RETURN
11590
11600 END
11610 SUBROUTINE OPUNCH (M,N,IMAX,DIST,AZIM)
11620 COMMON/INPUT/DS(50,20),DG(50,20),SS(50,20),SG(50,20),
11630 & SFGS(50,20),DFGS(50,20),TR(50,20),VA(50,20),DV(50,20)
11640 & ,SX(50),SY(50),SZ(50),GX(50),GY(50),GZ(50)
11650 COMMON/OUTPUT/VL(20,20),DL(20,20),SVL(20,20),K(20,20),TT(6)
11660 & ,VC(20,20)
11670 COMMON /CONSTA/ DELGS,VFIRST,VLAST,DLLAST,TITLE
11671 CHARACTER *60 TITLE
11680
11690 IOP1=2
11700 IOP2=0
11710 PUNCH 100,TITLE
11720 100 FORMAT(A60)
11730C PUNCH 110, IOP1,N,IOP2,M,DIST,AZIM,VFIRST,VLAST,DLLAST,IMAX
11740 PUNCH 110, IOP1,N,IOP2,M,DIST
11750 110 FORMAT (4I5,4F10,1,F5,0,15,F5,0)
11760 DC 200 J=1,M
11770 200 PUNCH 120, SZ(J),SX(J),SY(J),GZ(J),GX(J),GY(J),VC(J,N)
11780 120 FORMAT (6F10,2,10X,F10,0)
11790C PUNCH 130, (VL(I,N),I=1,IMAX)
11800C PUNCH 130, (DL(I,N),I=1,IMAX=1)
11810 130 FORMAT ((8F10,1))
11820
11830 RETURN
11840 END

```